US009477082B2

(12) **United States Patent**
Huang et al.

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(45) **Date of Patent: Oct. 25, 2016**

(54) **ANGULAR DISPLACEMENT DETECTING METHOD FOR ADAPTIVE OPTICS SYSTEM, IMAGING MAGNIFICATION DETECTING METHOD FOR ADAPTIVE OPTICS SYSTEM, AND ADAPTIVE OPTICS SYSTEM**

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(72) Inventors: **Hongxin Huang**, Hamamatsu (JP); **Takashi Inoue**, Hamamatsu (JP)

(73) Assignee: **HAMAMATSU PHOTONICS K.K.**, Hamamatsu-shi, Shizuoka (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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§ 371 (c)(1),
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PCT Pub. Date: **Dec. 11, 2014**

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Jun. 6, 2013 (JP) 2013-119851

(51) **Int. Cl.**
G02F 1/01 (2006.01)
G02F 1/03 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***G02B 27/0068*** (2013.01); ***A61B 3/1015*** (2013.01); ***A61B 3/12*** (2013.01);
(Continued)

(58) **Field of Classification Search**
USPC 359/239, 240, 559–564, 276, 278, 279, 359/245
See application file for complete search history.

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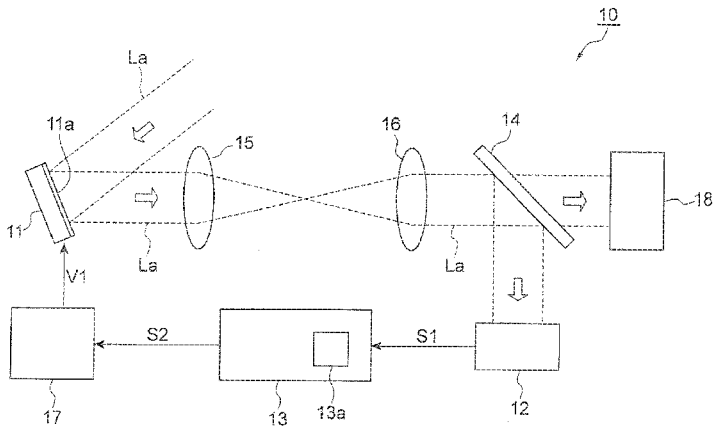
Primary Examiner — Mohammed Hasan
(74) *Attorney, Agent, or Firm* — Drinker Biddle & Reath LLP

(57) **ABSTRACT**

An adaptive optics system includes a spatial light modulator configured to spatially modulate a phase of an optical image incident on a modulation surface and a wavefront sensor including a lens array having a plurality of two-dimensionally arranged lenses and an optical detection element for detecting a light intensity distribution including converging spots formed by the lens array and configured to receive the optical image after the modulation from the spatial light modulator, and compensates for wavefront distribution by controlling a phase pattern displayed in the spatial light modulator based on a wavefront shape of the optical image obtained from the light intensity distribution, wherein an amount of angular displacement between the modulation surface and the wavefront sensor is calculated.

16 Claims, 39 Drawing Sheets



(51) **Int. Cl.**

G02B 27/00	(2006.01)
G01J 9/00	(2006.01)
G01M 11/00	(2006.01)
A61B 3/10	(2006.01)
A61B 3/12	(2006.01)
G01J 1/44	(2006.01)
G01M 11/02	(2006.01)
G02B 27/09	(2006.01)
G02B 3/00	(2006.01)

(52) **U.S. Cl.**

CPC . ***G01J 1/44*** (2013.01); ***G01J 9/00*** (2013.01); ***G01M 11/00*** (2013.01); ***G01M 11/02*** (2013.01); ***G02B 27/0927*** (2013.01); *G02B 3/0006* (2013.01); *G02F 2203/12* (2013.01); *G02F 2203/18* (2013.01)

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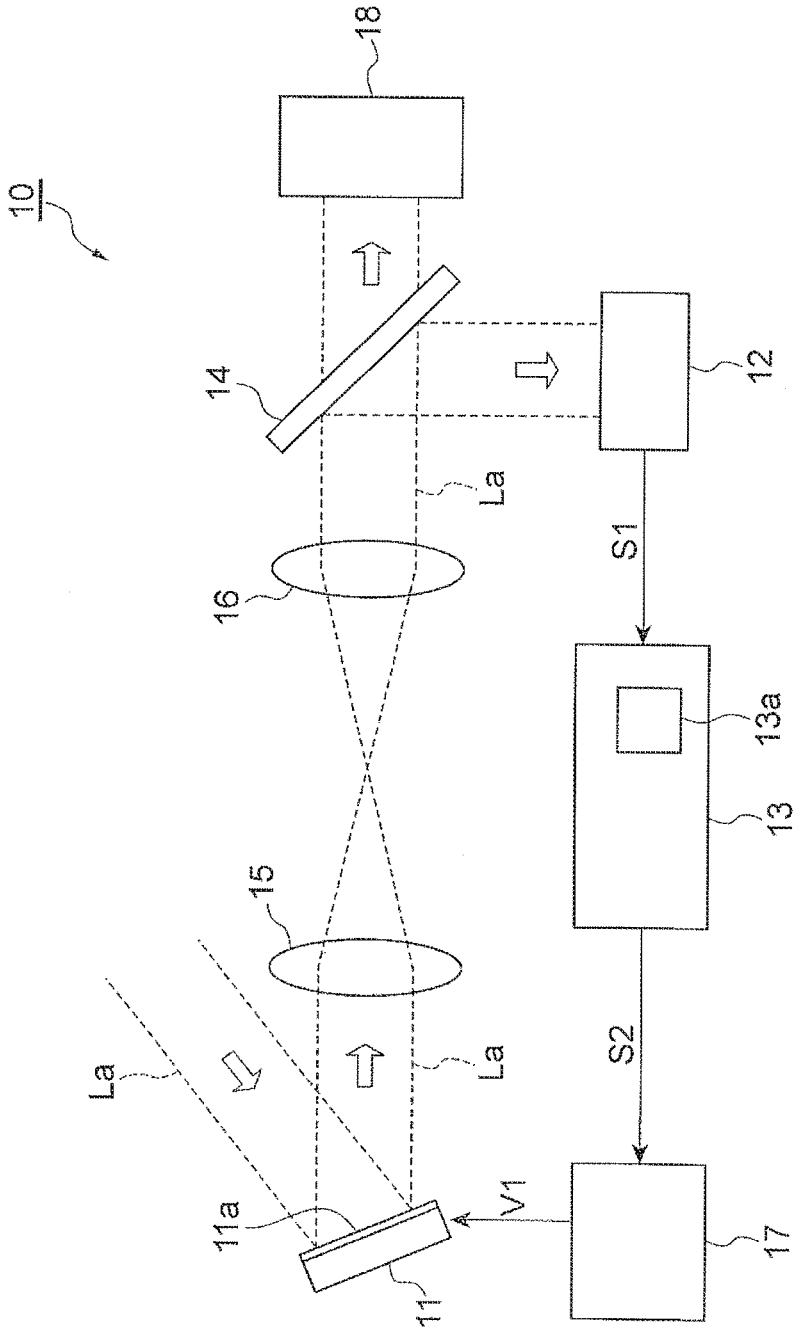
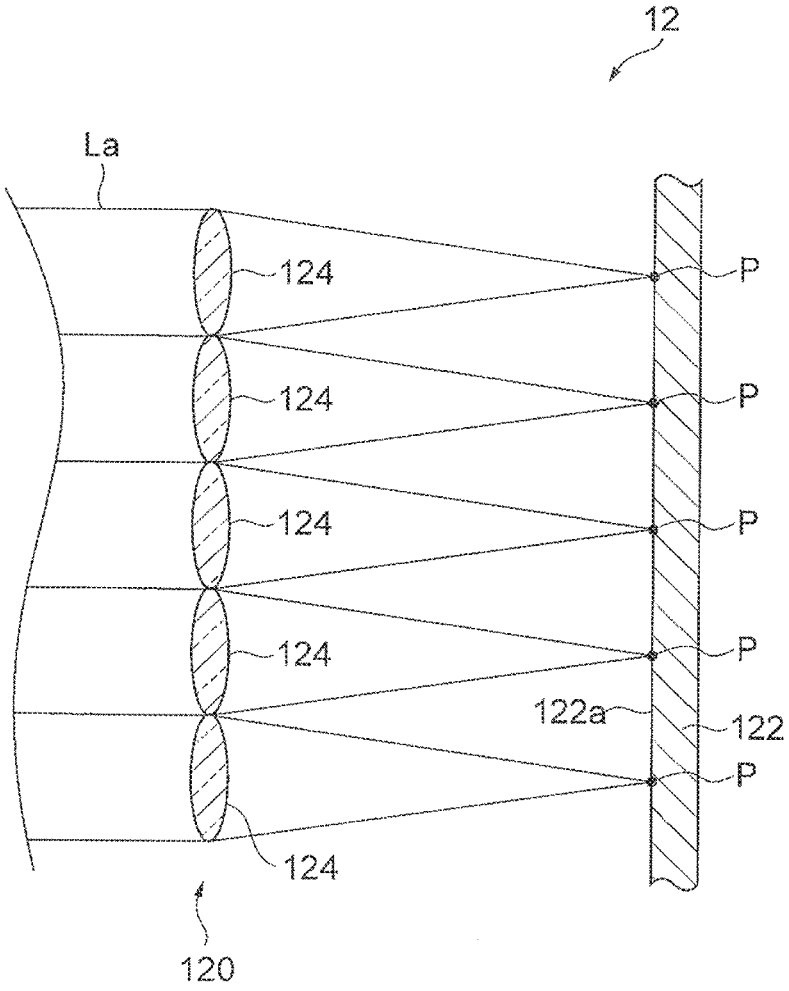


Fig.1

Fig.2



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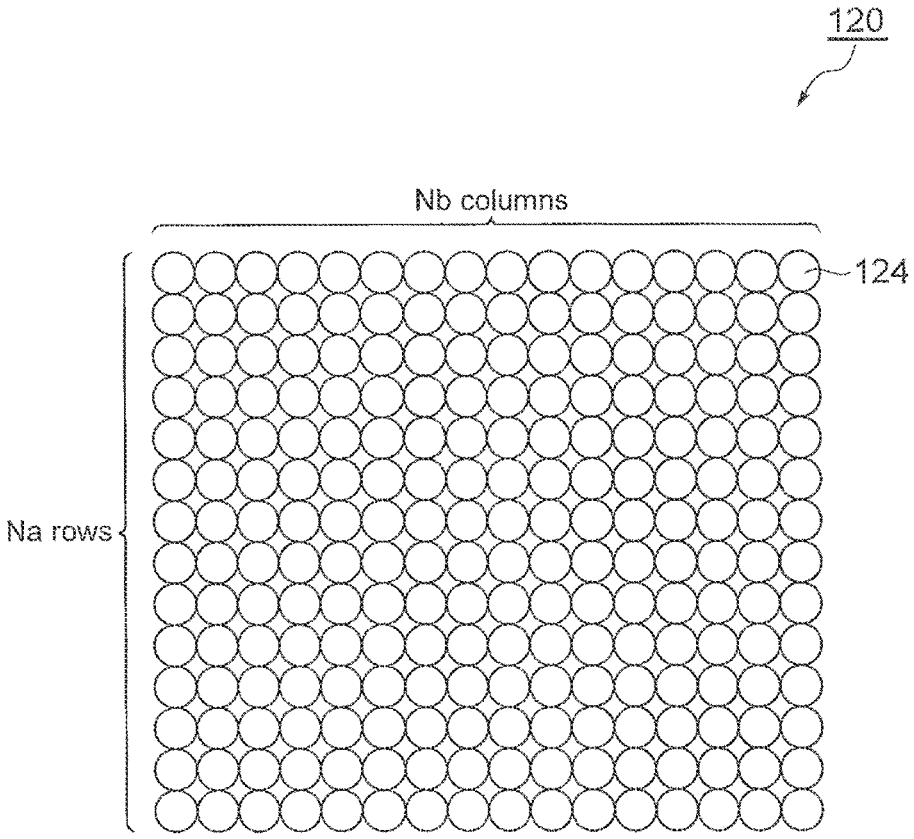

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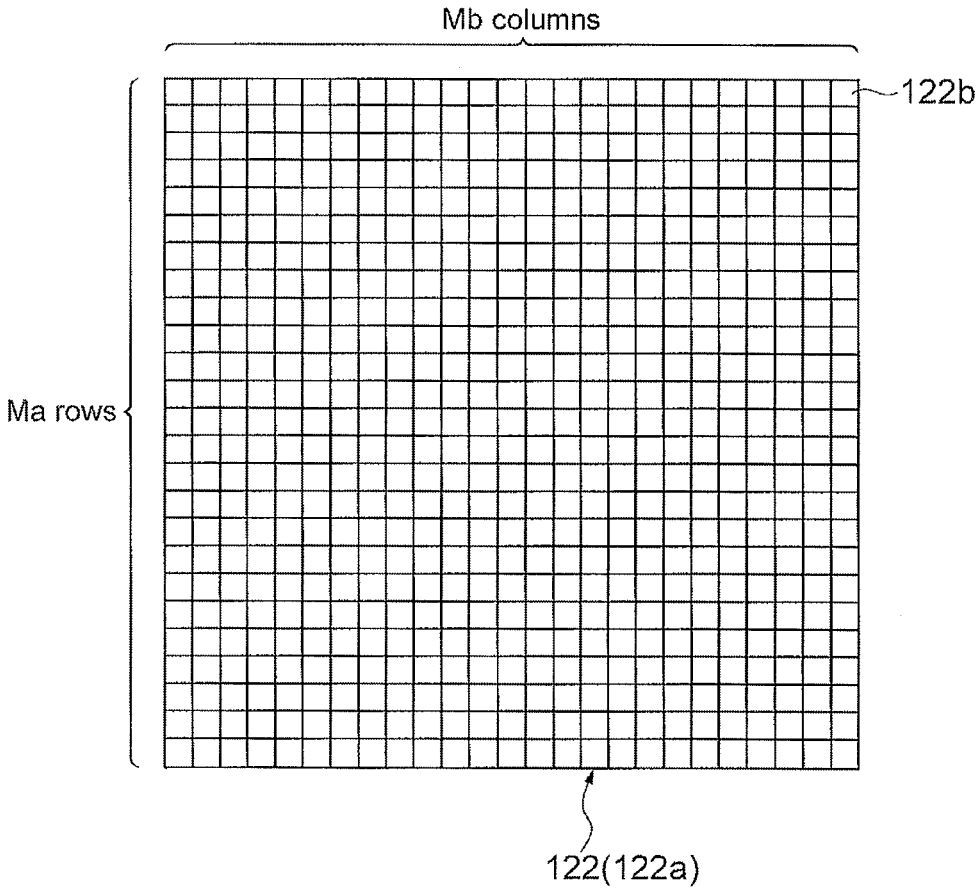

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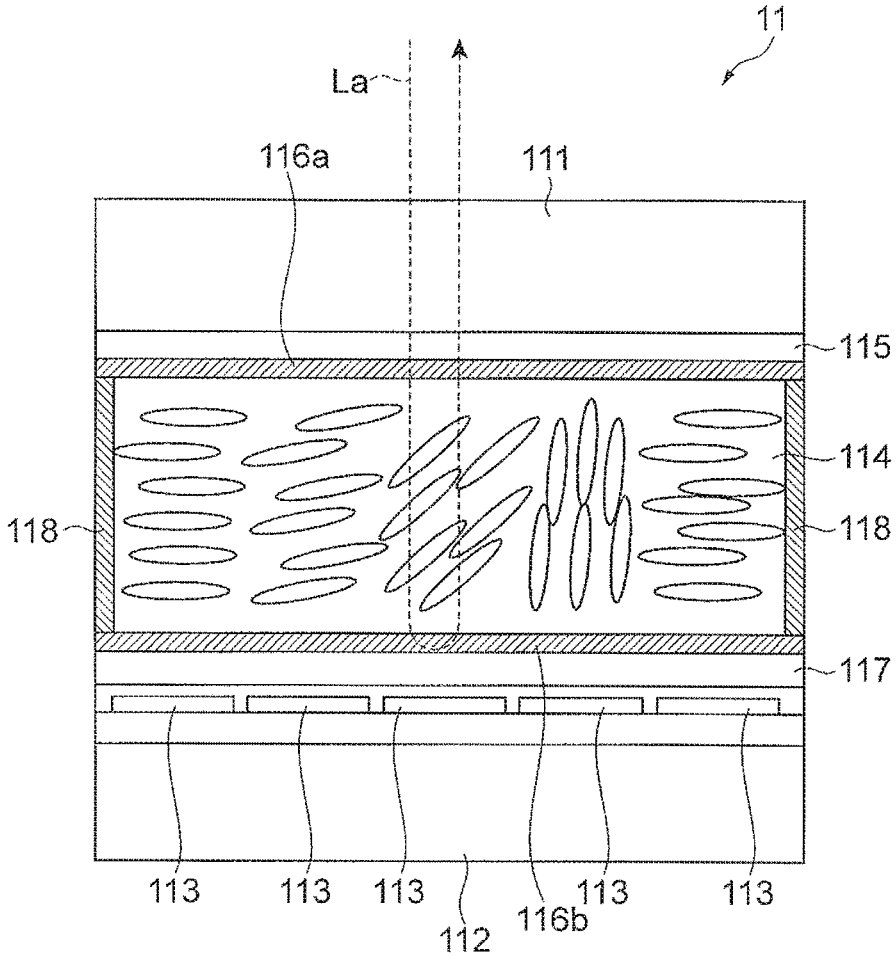

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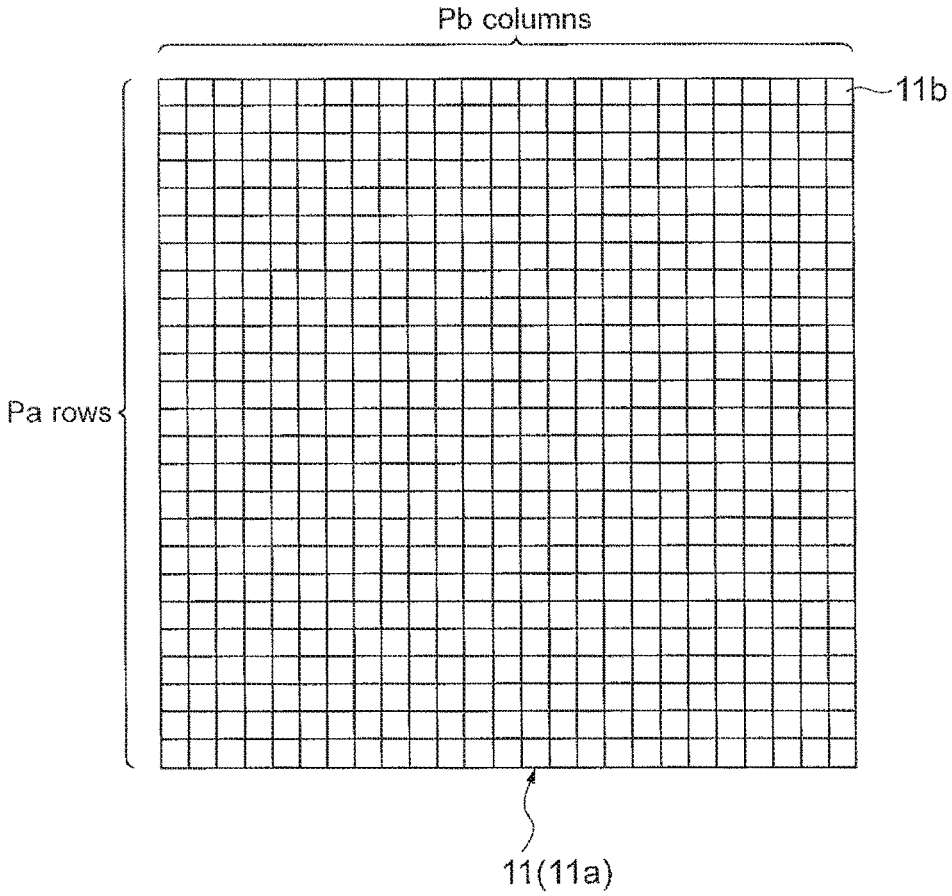


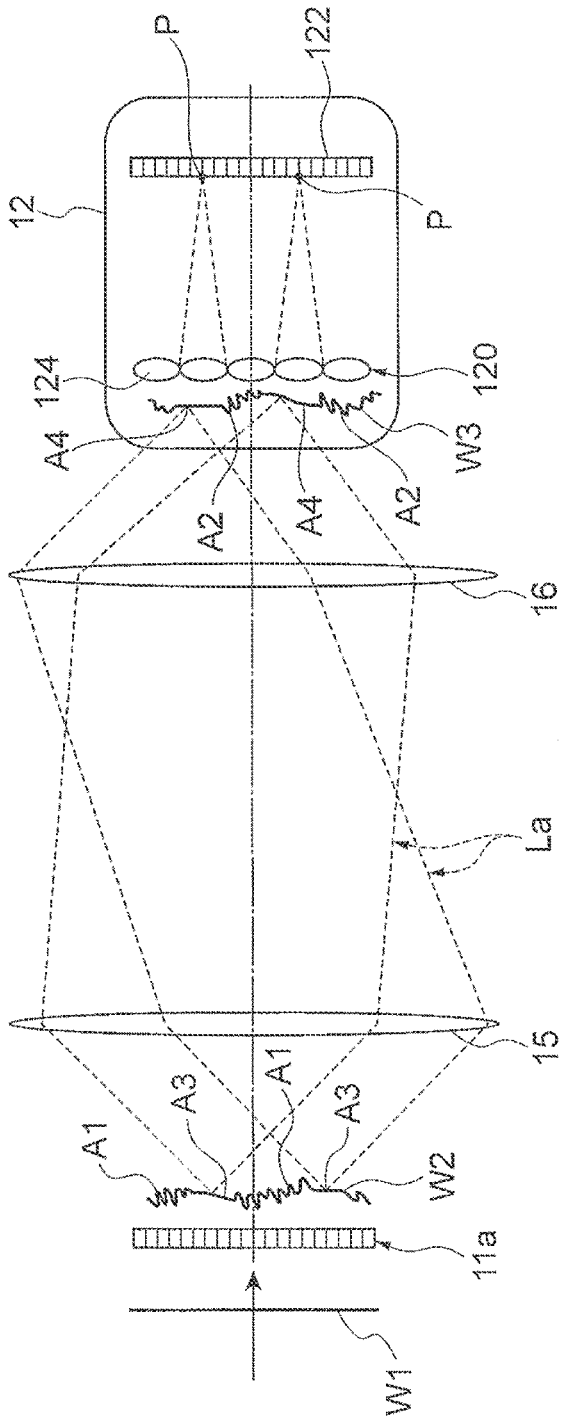
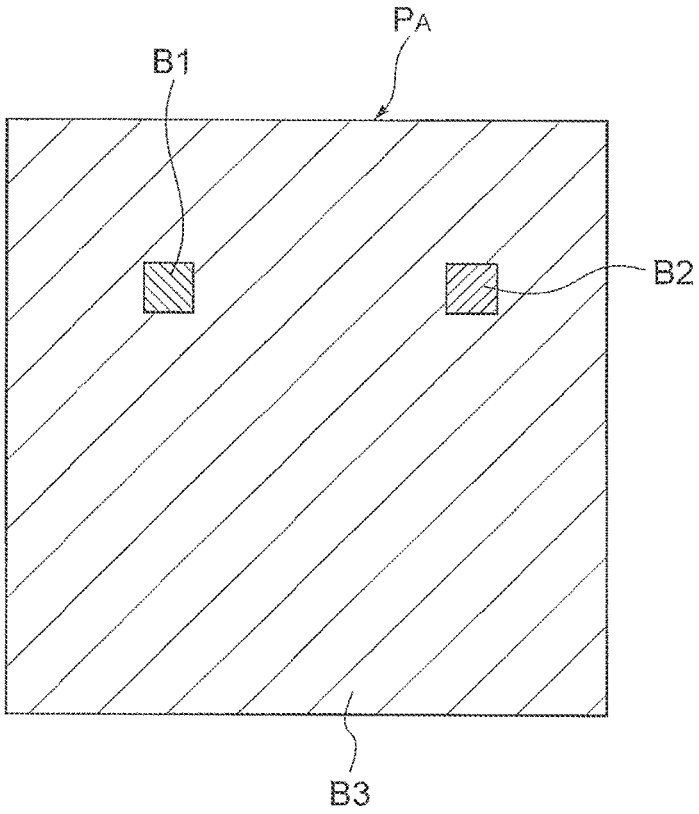


Fig.7

Fig.8



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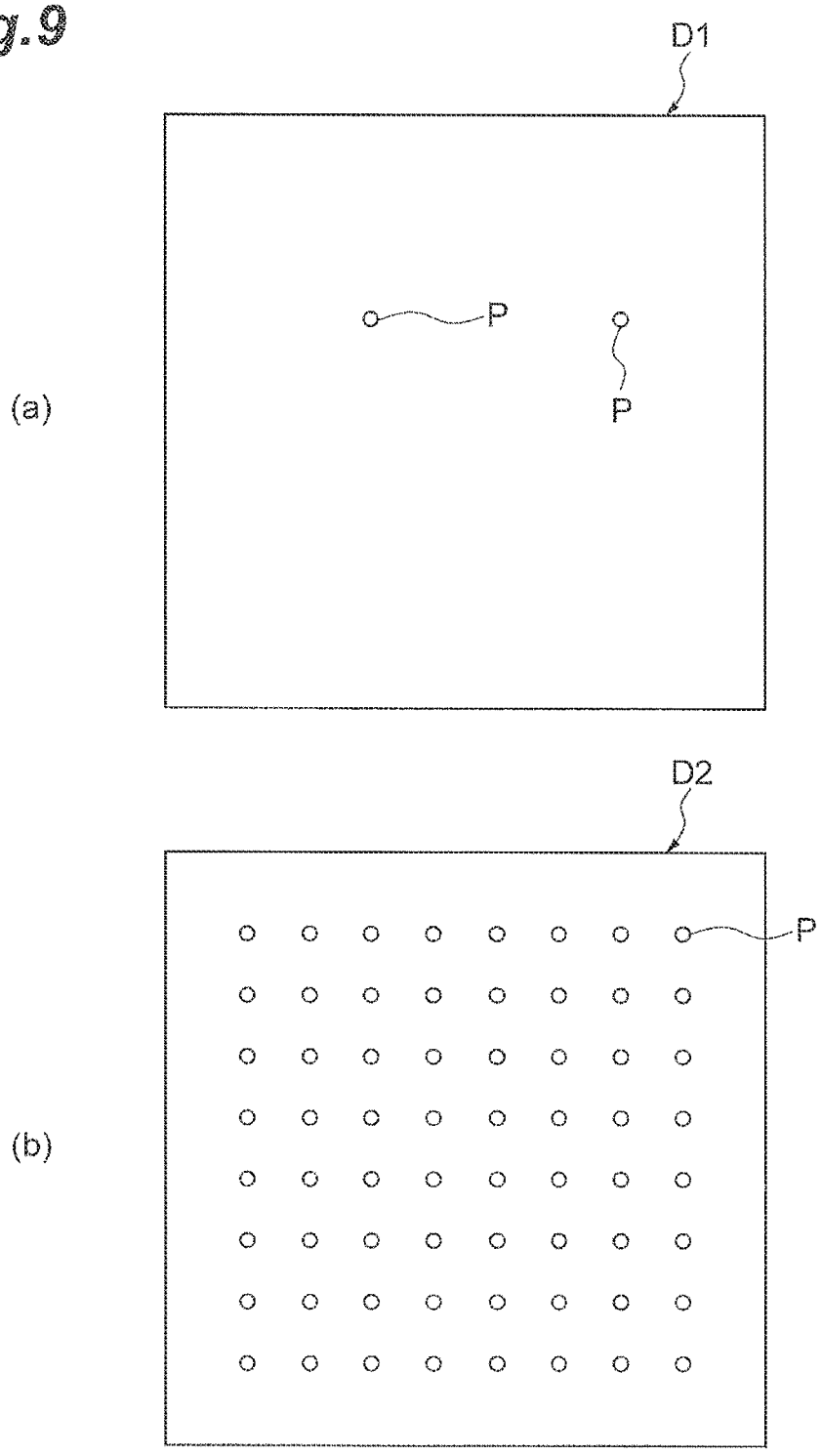
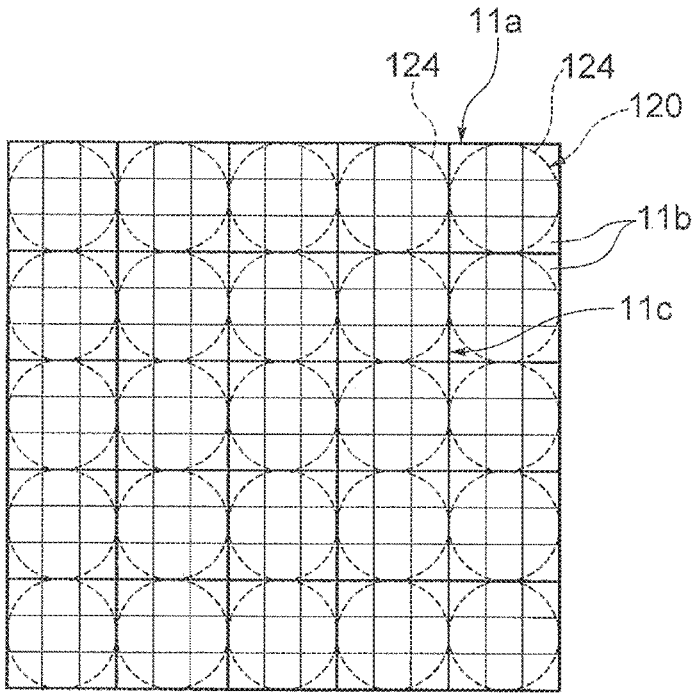


Fig.10

(a)



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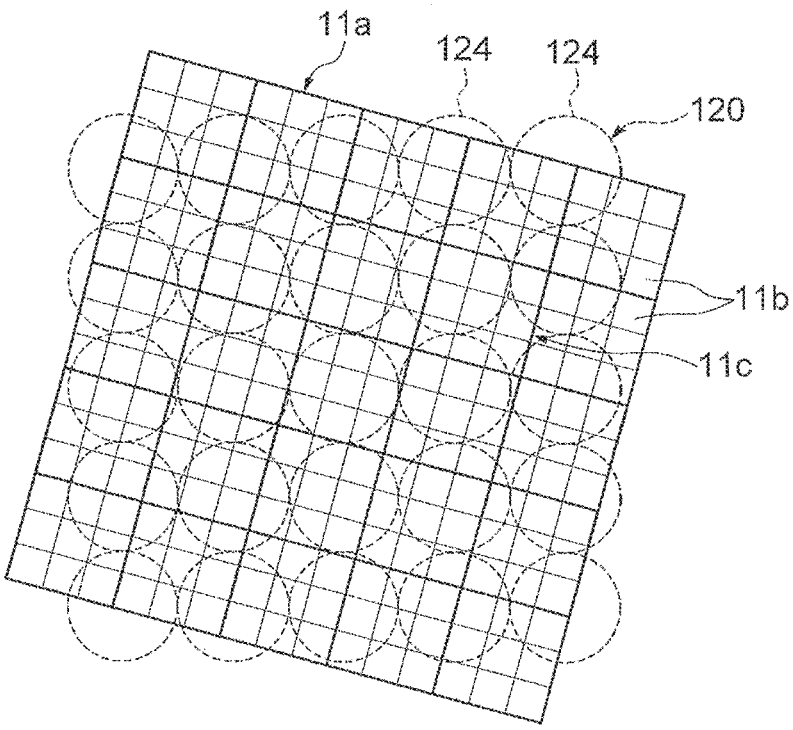

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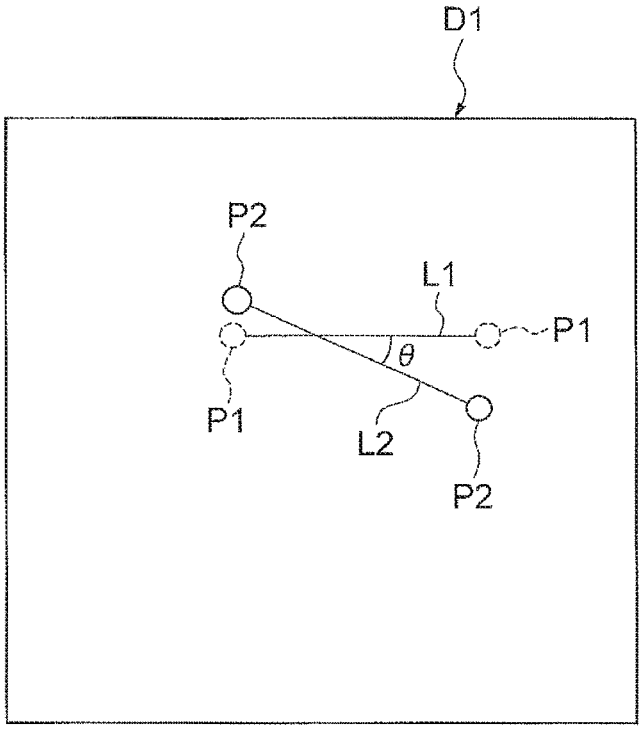

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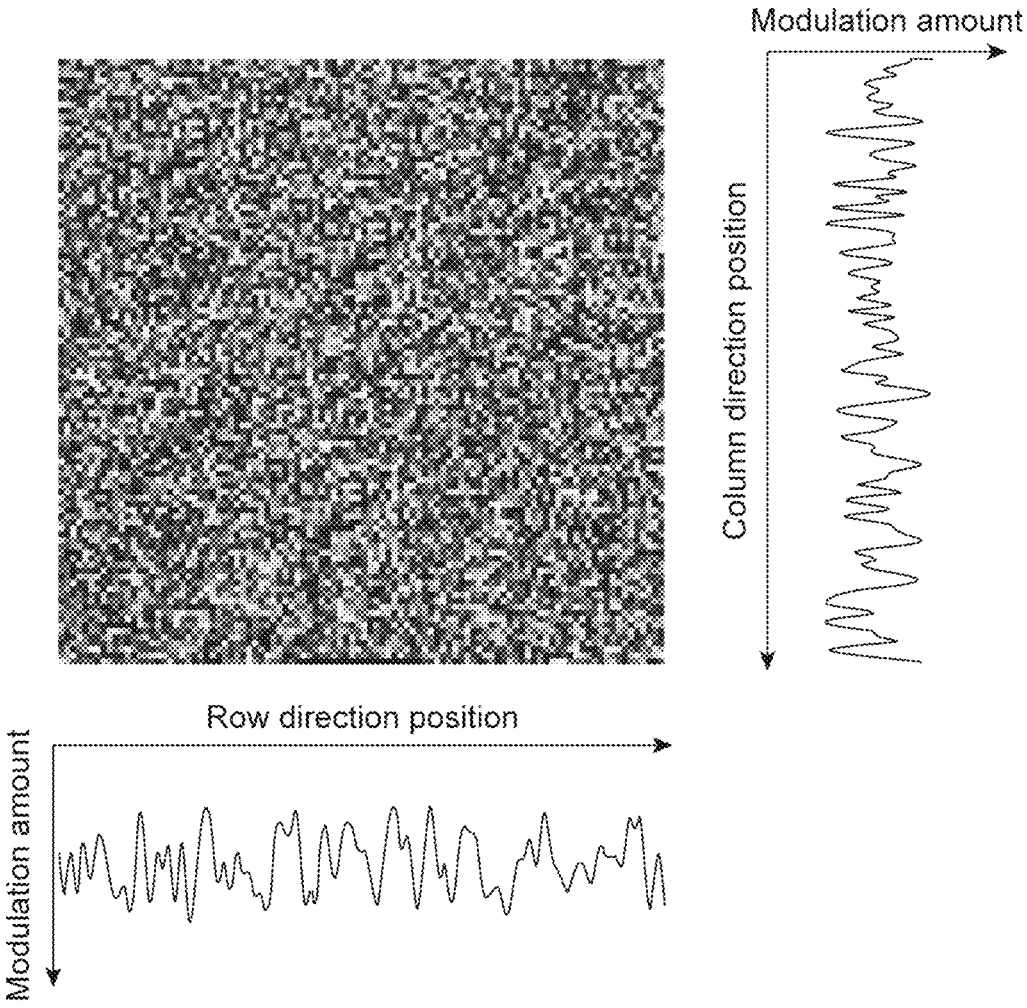
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Row direction position
Modulation amount

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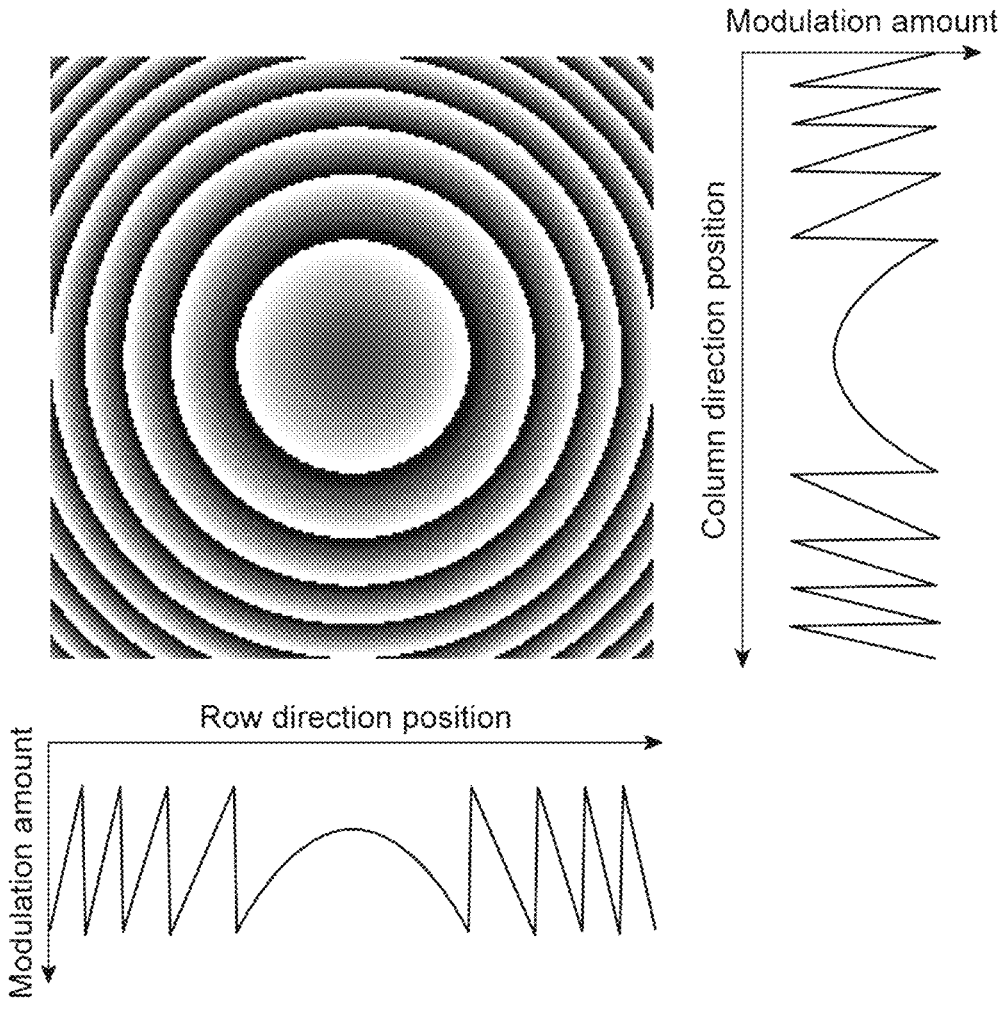
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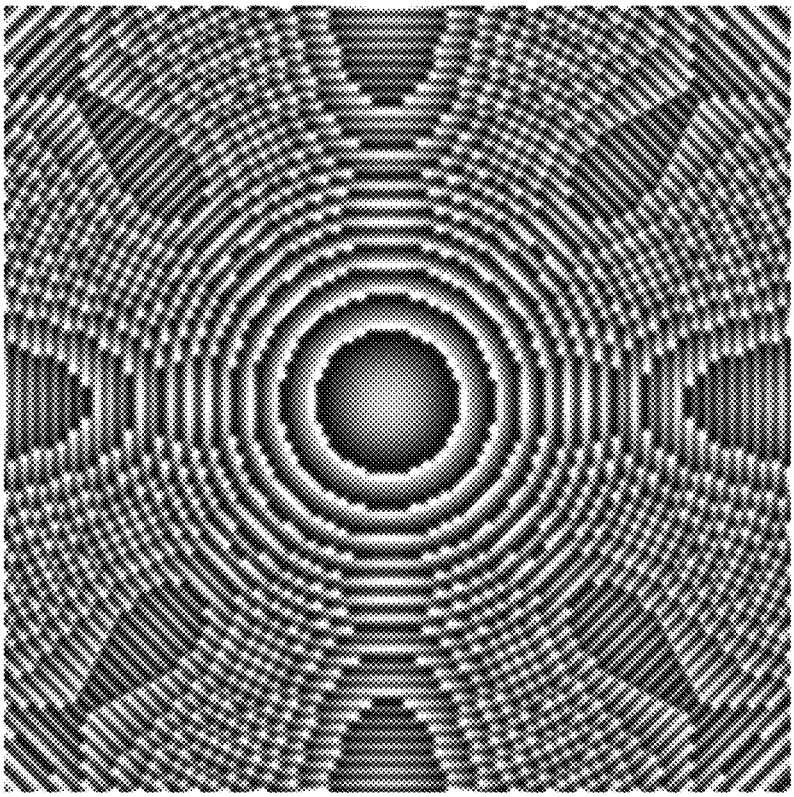

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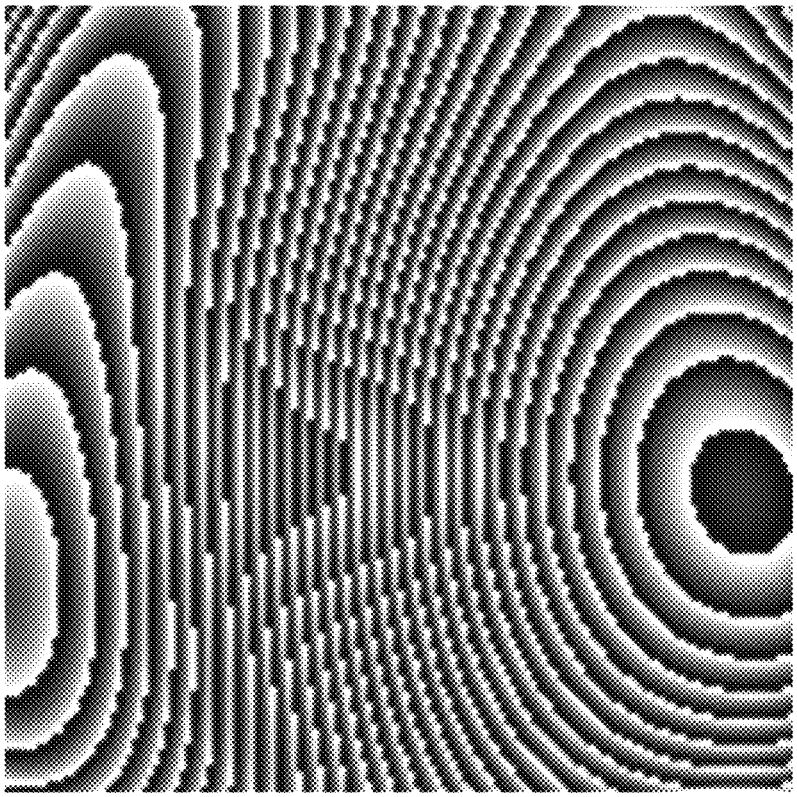

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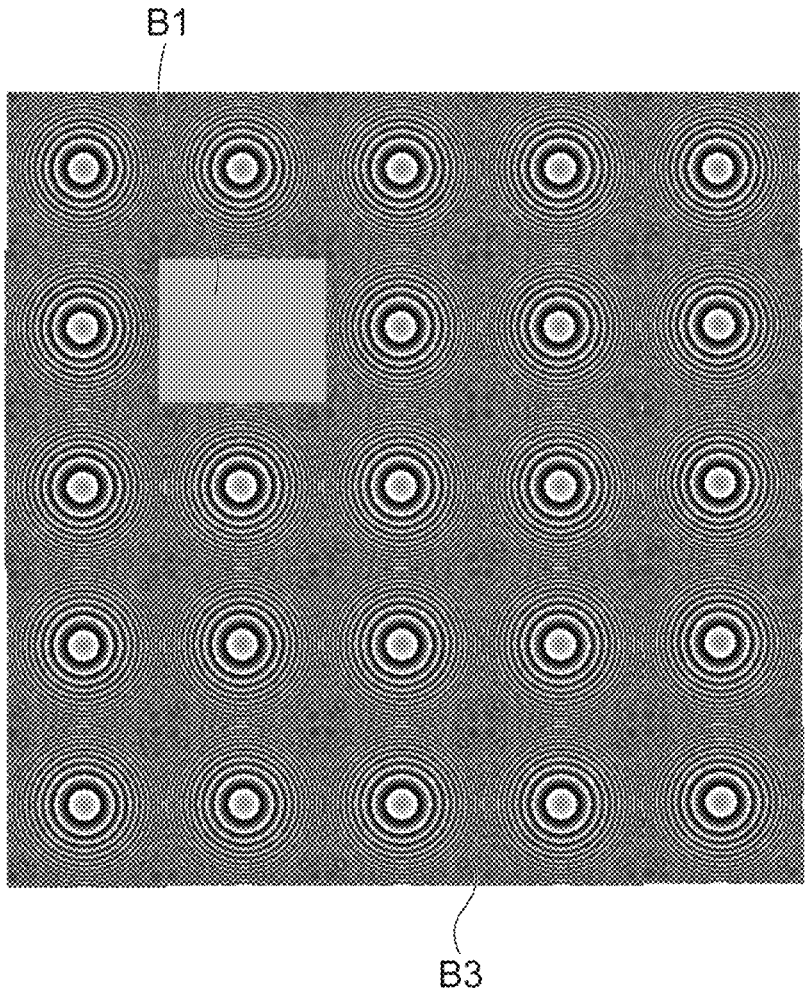

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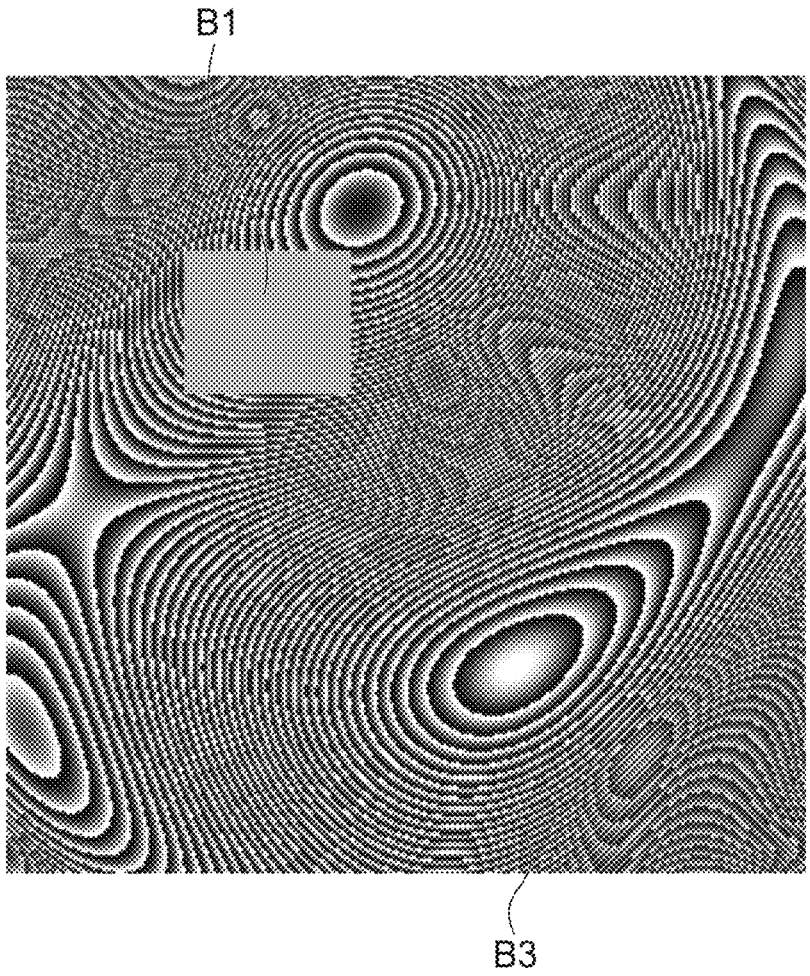

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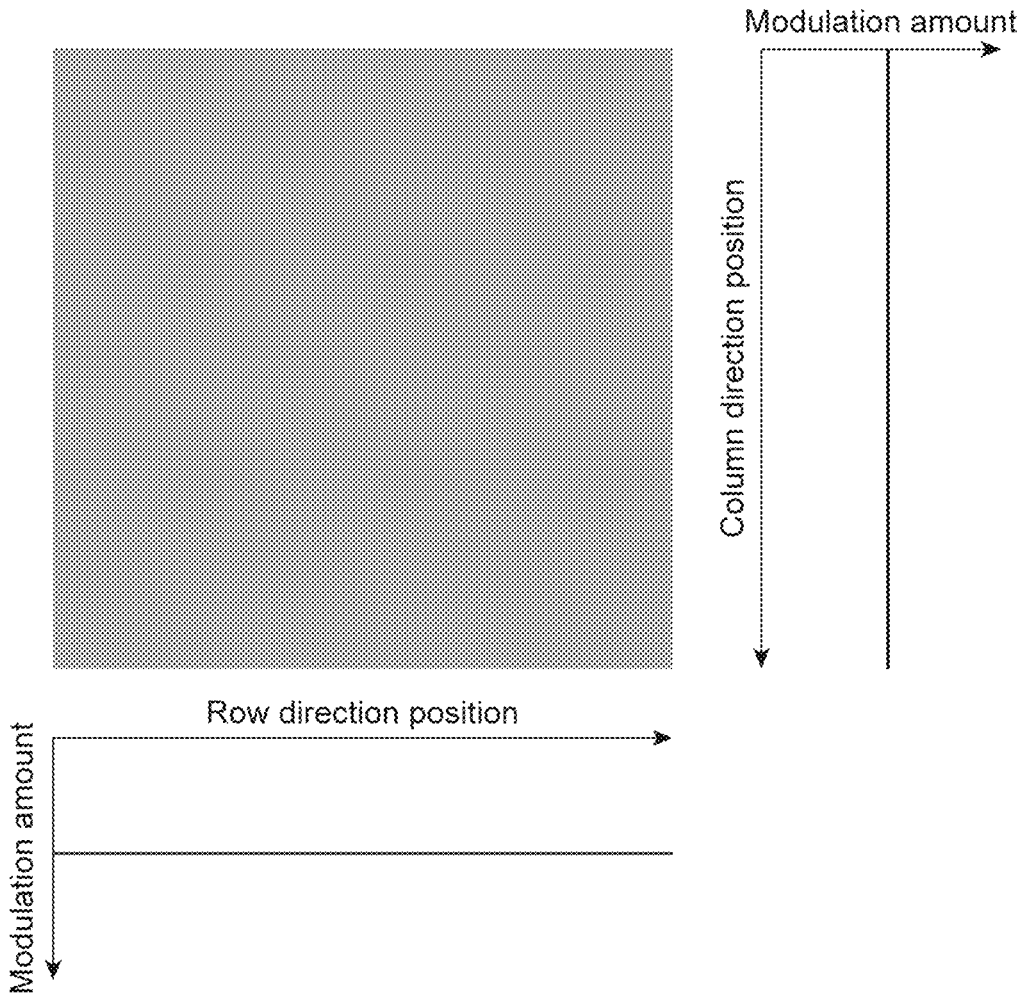
Modulation amount
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Modulation amount

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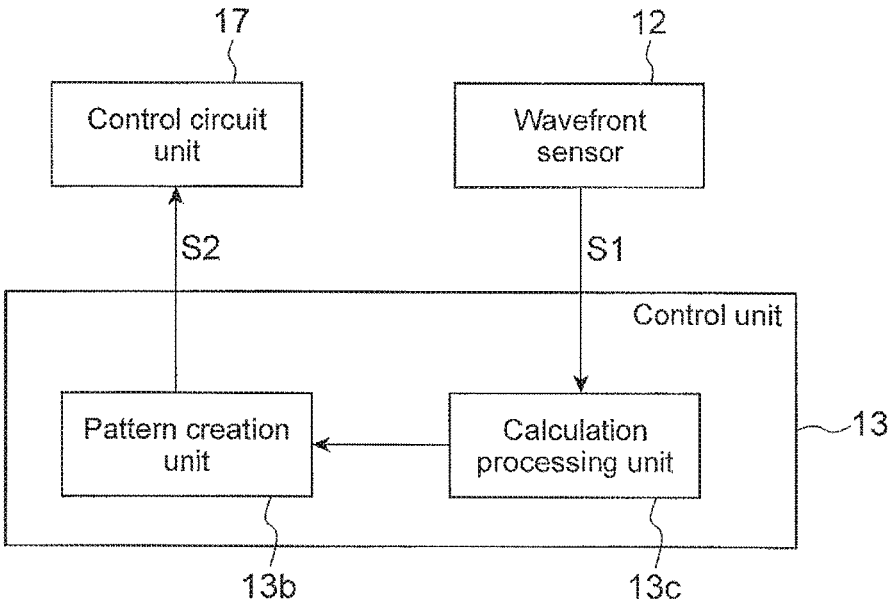

17
12
Control circuit unit
Wavefront sensor
S2
S1
Control unit
Pattern creation unit
Calculation processing unit
13
13b
13c

Fig.20

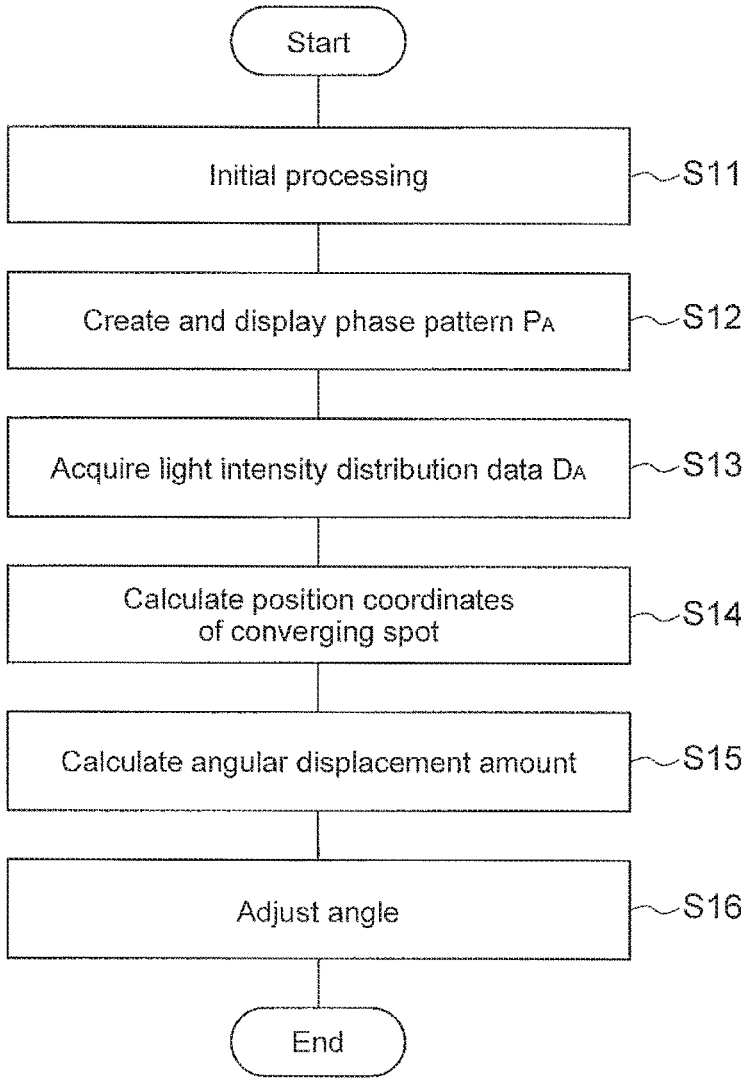

Start
Initial processing
S11
Create and display phase pattern PA
S12
Acquire light intensity distribution data DA
S13
Calculate position coordinates of converging spot
S14
Calculate angular displacement amount
S15
Adjust angle
S16
End

Fig.21

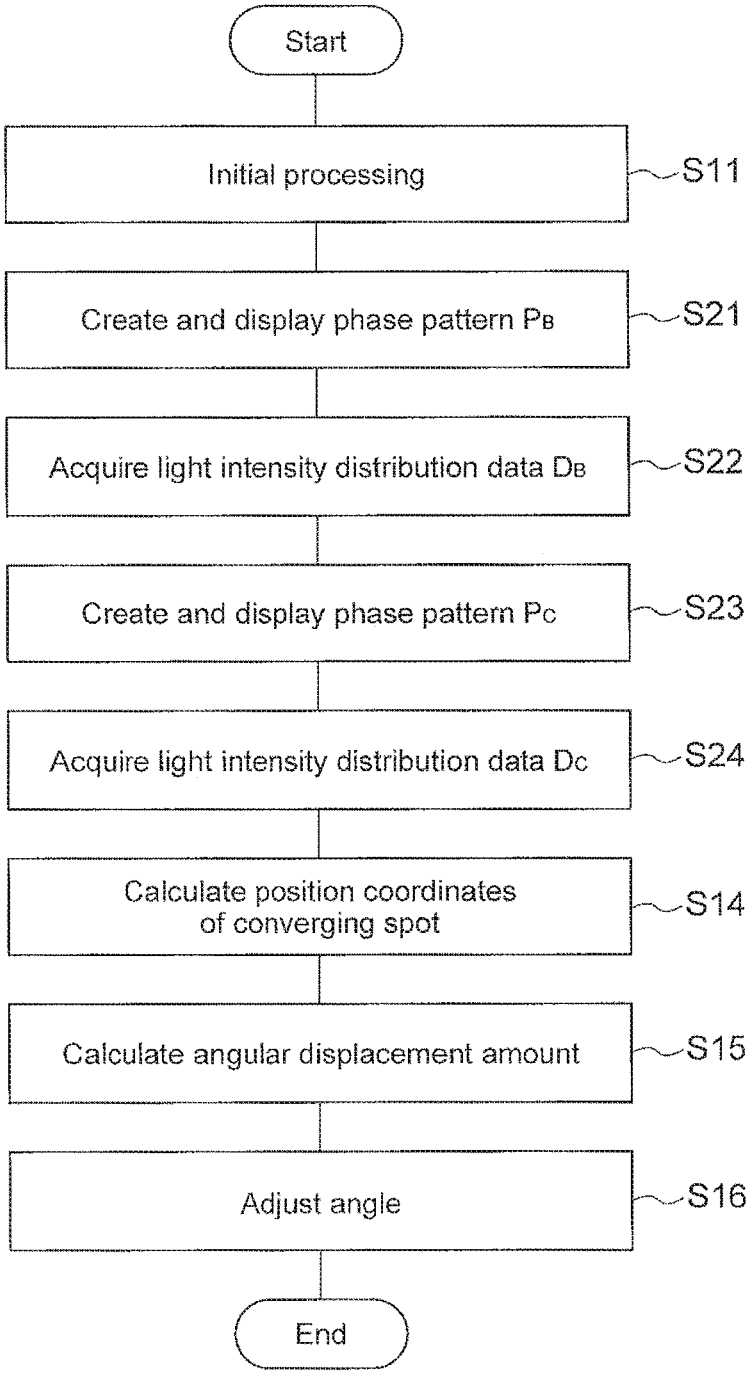
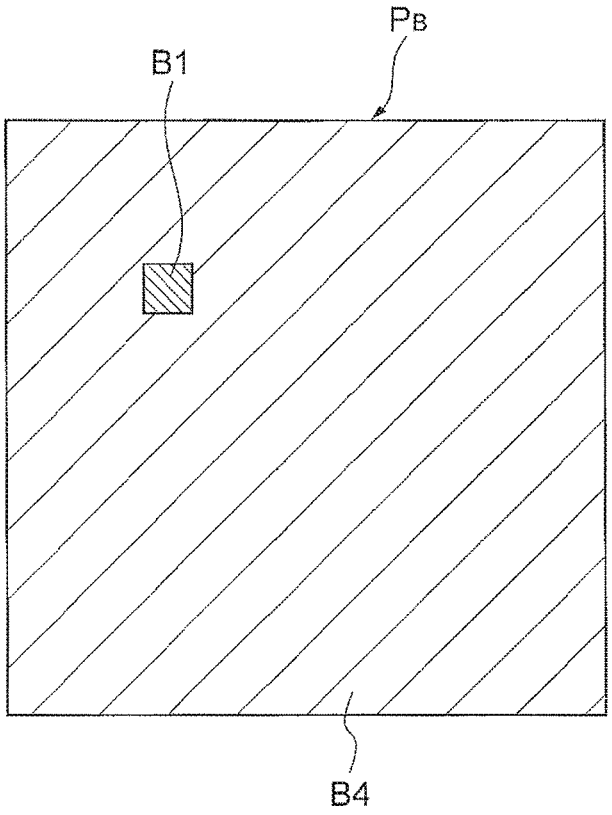

Start
Initial processing
S11
Create and display phase pattern PB
S21
Acquire light intensity distribution data DB
S22
Create and display phase pattern PC
S23
Acquire light intensity distribution data DC
S24
Calculate position coordinates of converging spot
S14
Calculate angular displacement amount
S15
Adjust angle
S16
End

Fig.22



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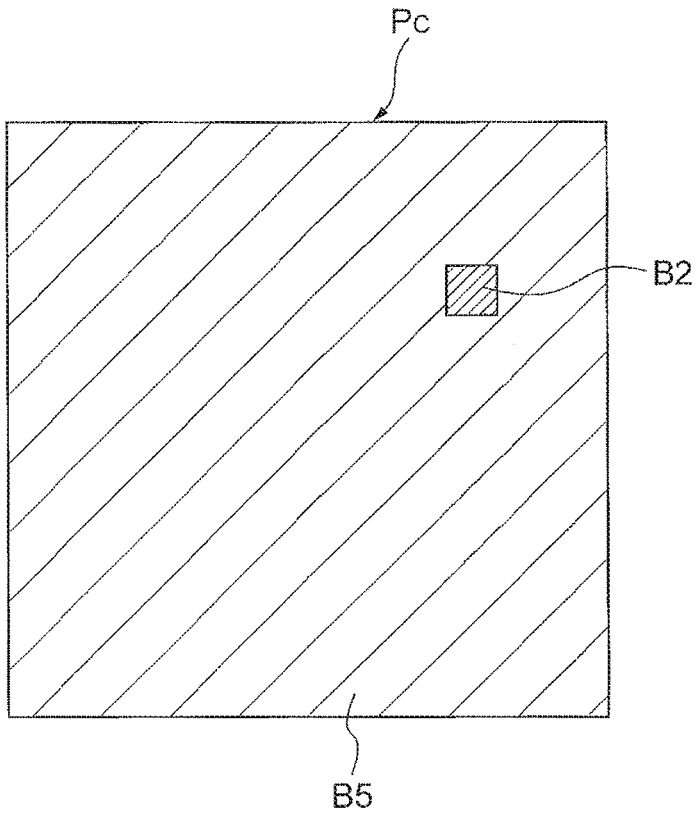

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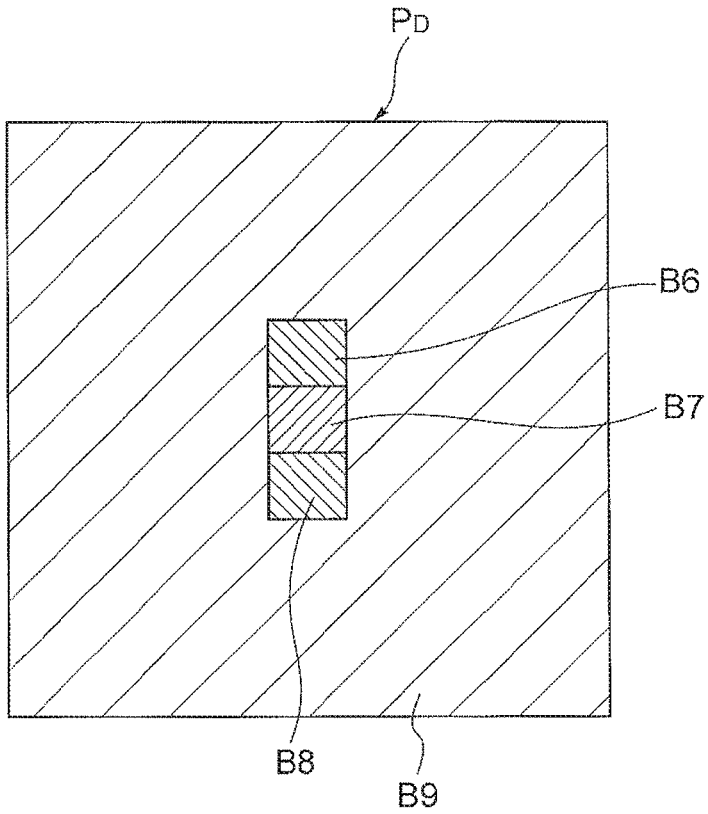

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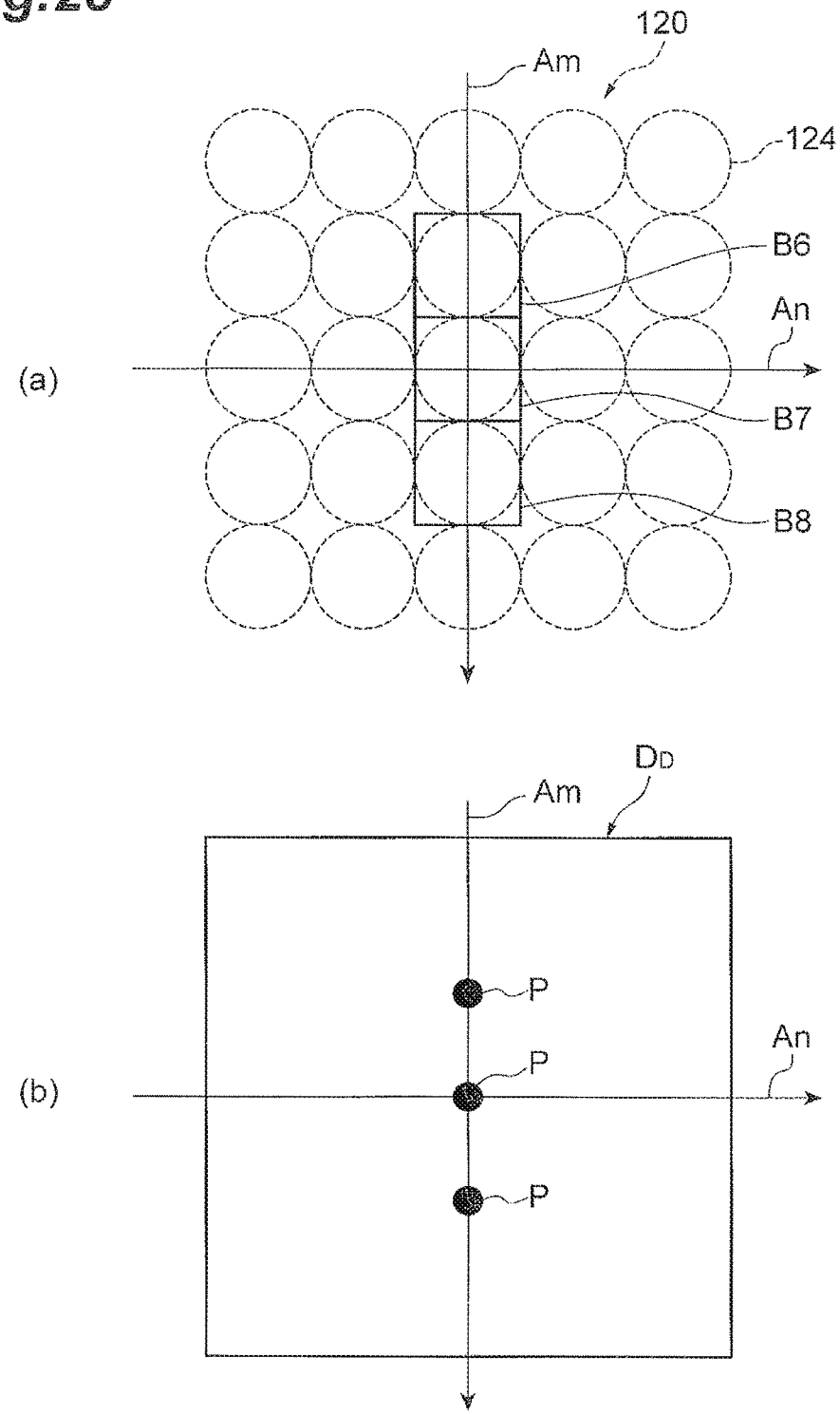

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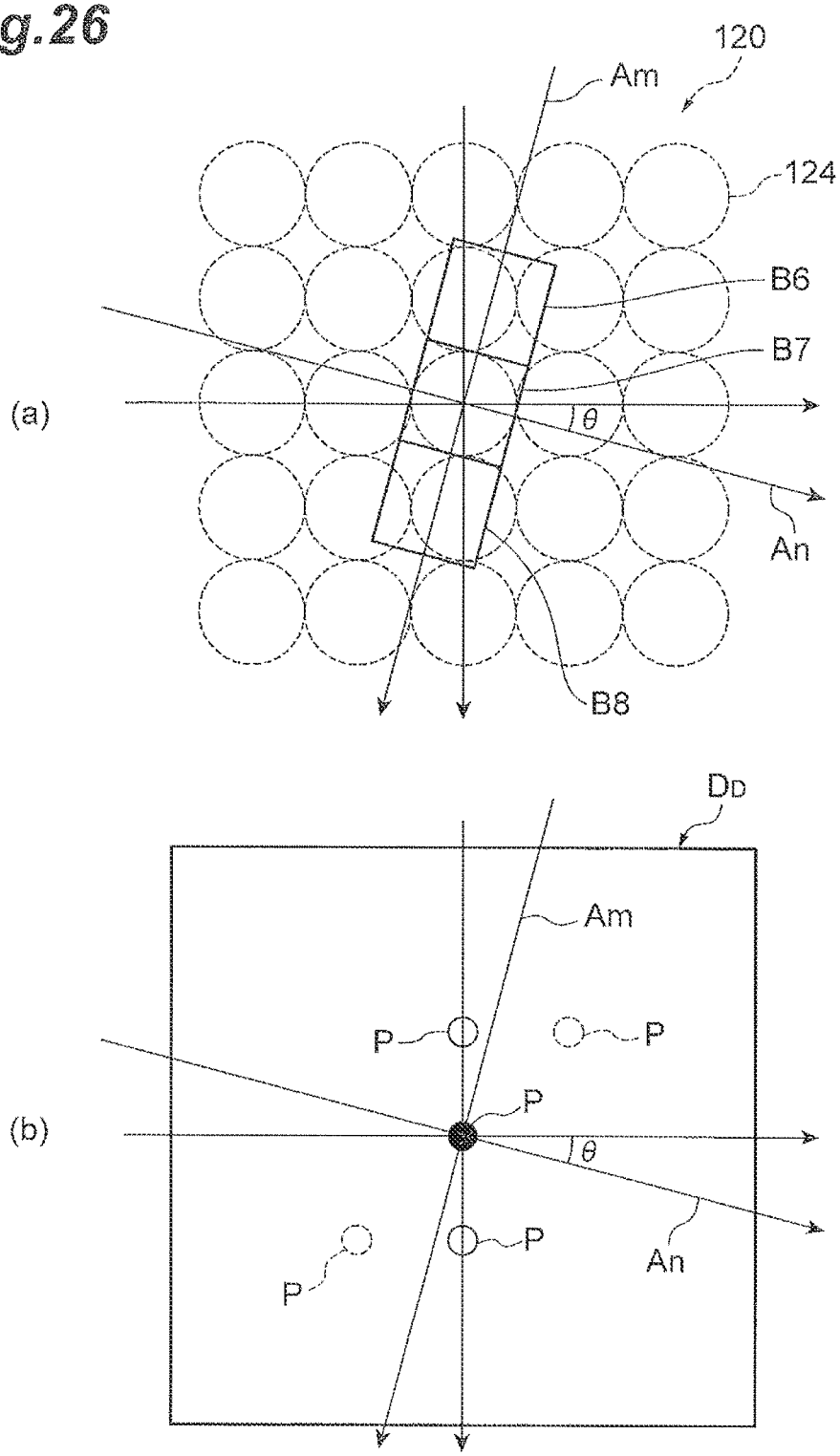

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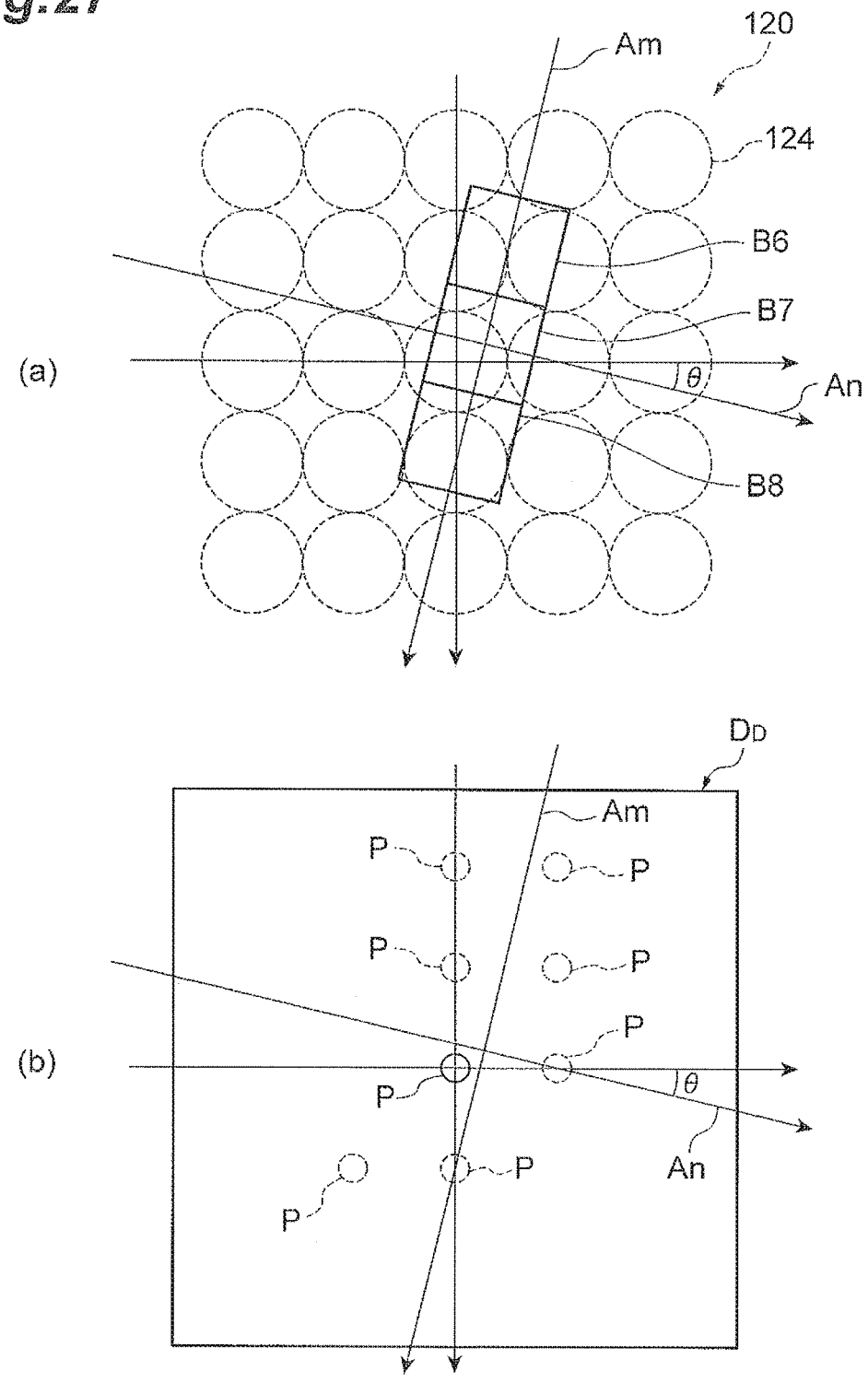

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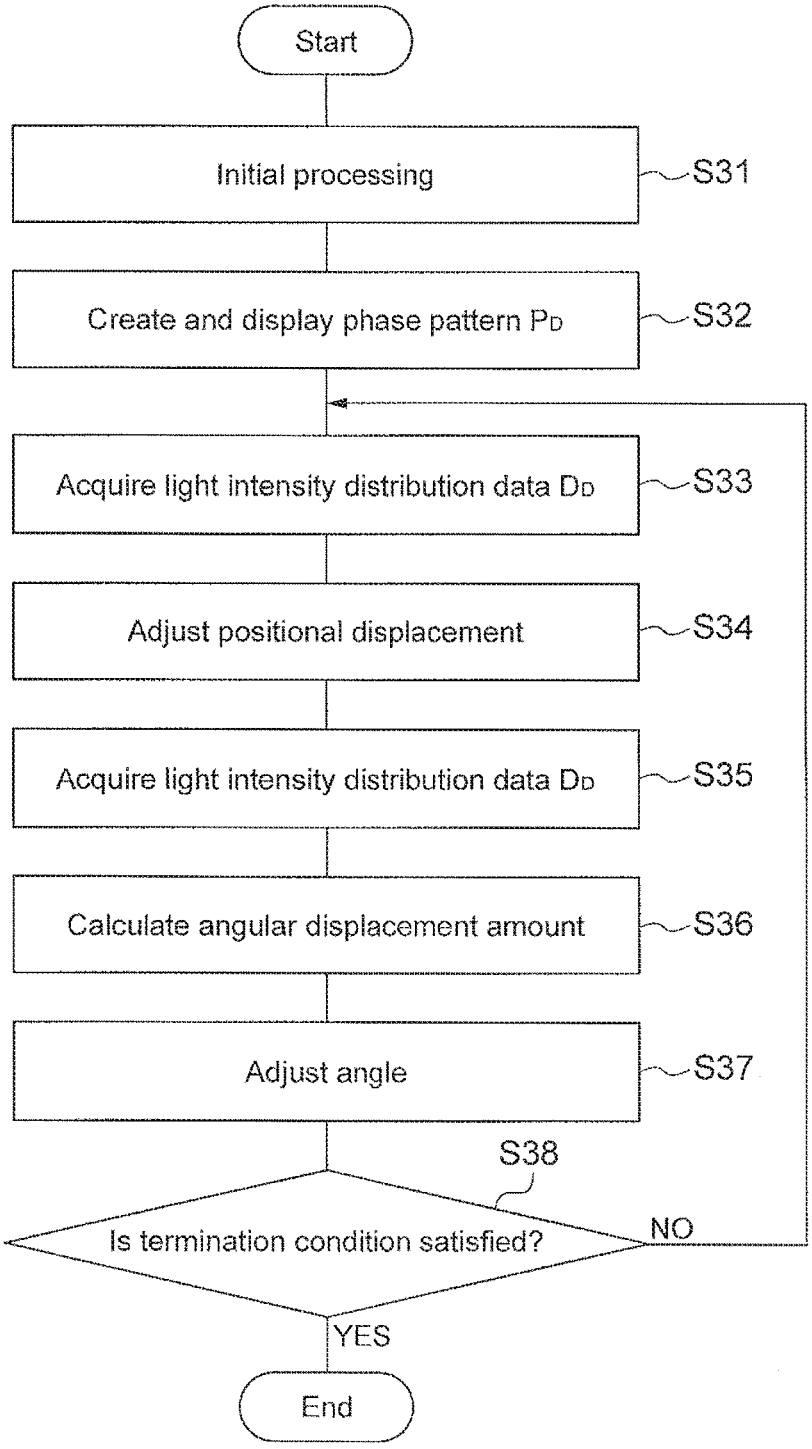
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Initial processing
S31
Create and display phase pattern PD
S32
Acquire light intensity distribution data DD
S33
Adjust positional displacement
S34
Acquire light intensity distribution data DD
S35
Calculate angular displacement amount
S36
Adjust angle
S37
S38
Is termination condition satisfied?
NO
YES
End

Fig.29

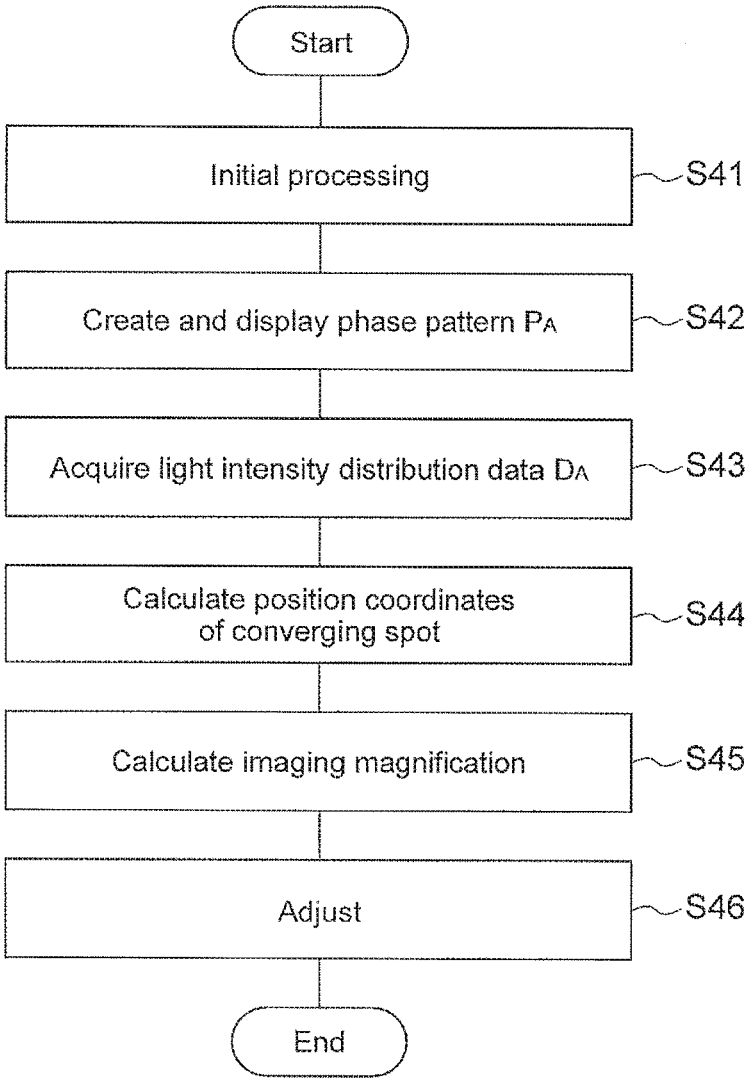

Start
Initial processing
S41
Create and display phase pattern P_A
S42
Acquire light intensity distribution data D_A
S43
Calculate position coordinates of converging spot
S44
Calculate imaging magnification
S45
Adjust
S46
End

Fig.30

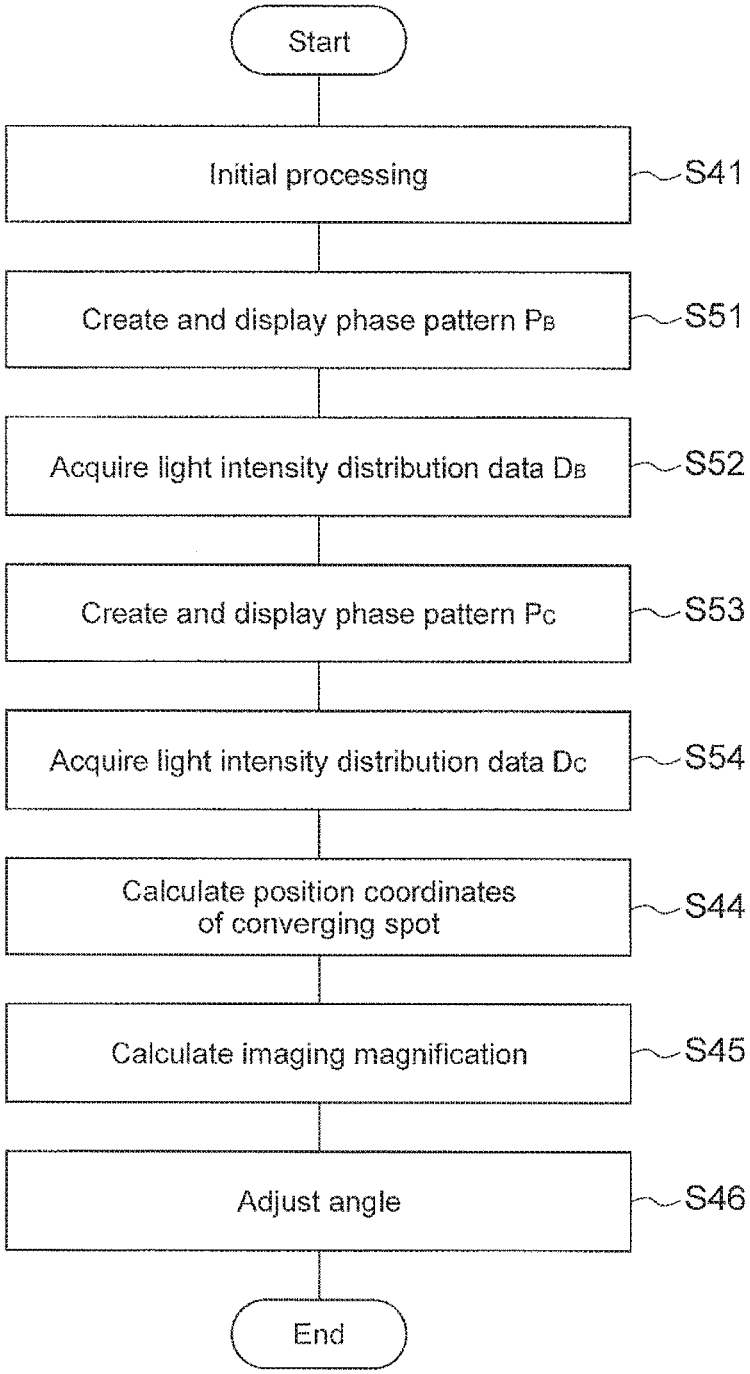
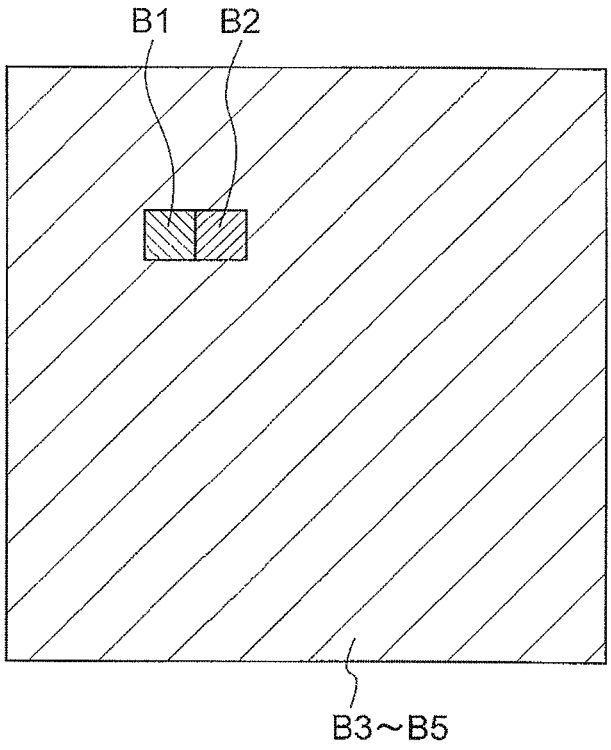

Start
Initial processing
S41
Create and display phase pattern PB
S51
Acquire light intensity distribution data DB
S52
Create and display phase pattern PC
S53
Acquire light intensity distribution data DC
S54
Calculate position coordinates of converging spot
S44
Calculate imaging magnification
S45
Adjust angle
S46
End

Fig.31

(a)



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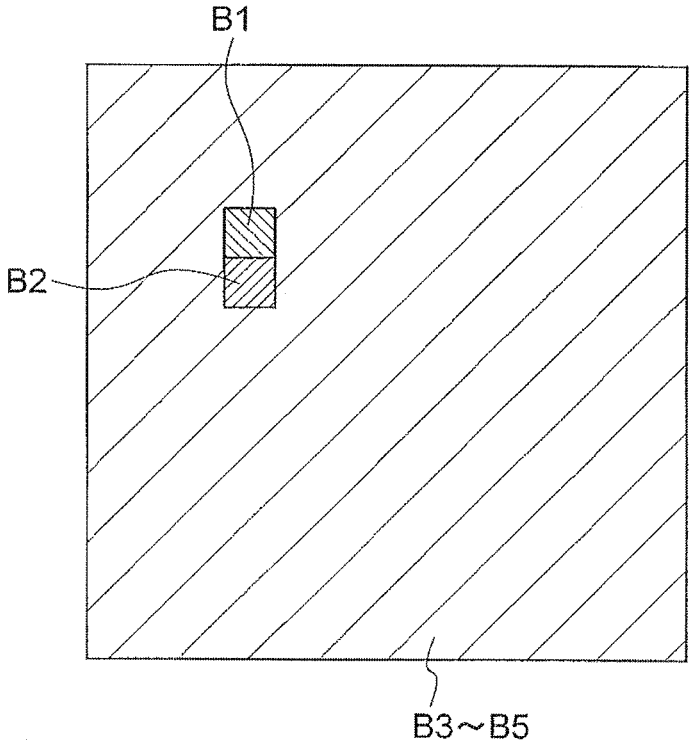

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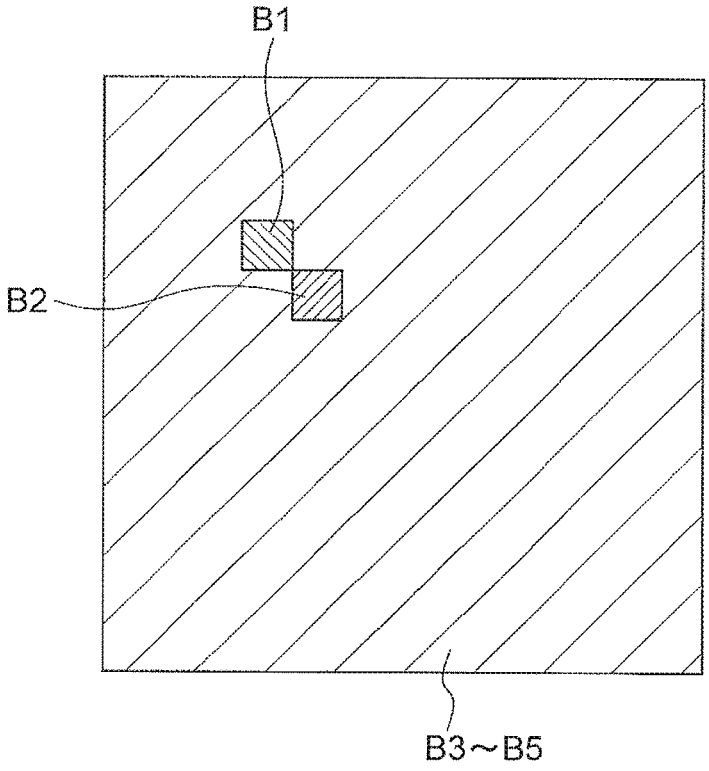

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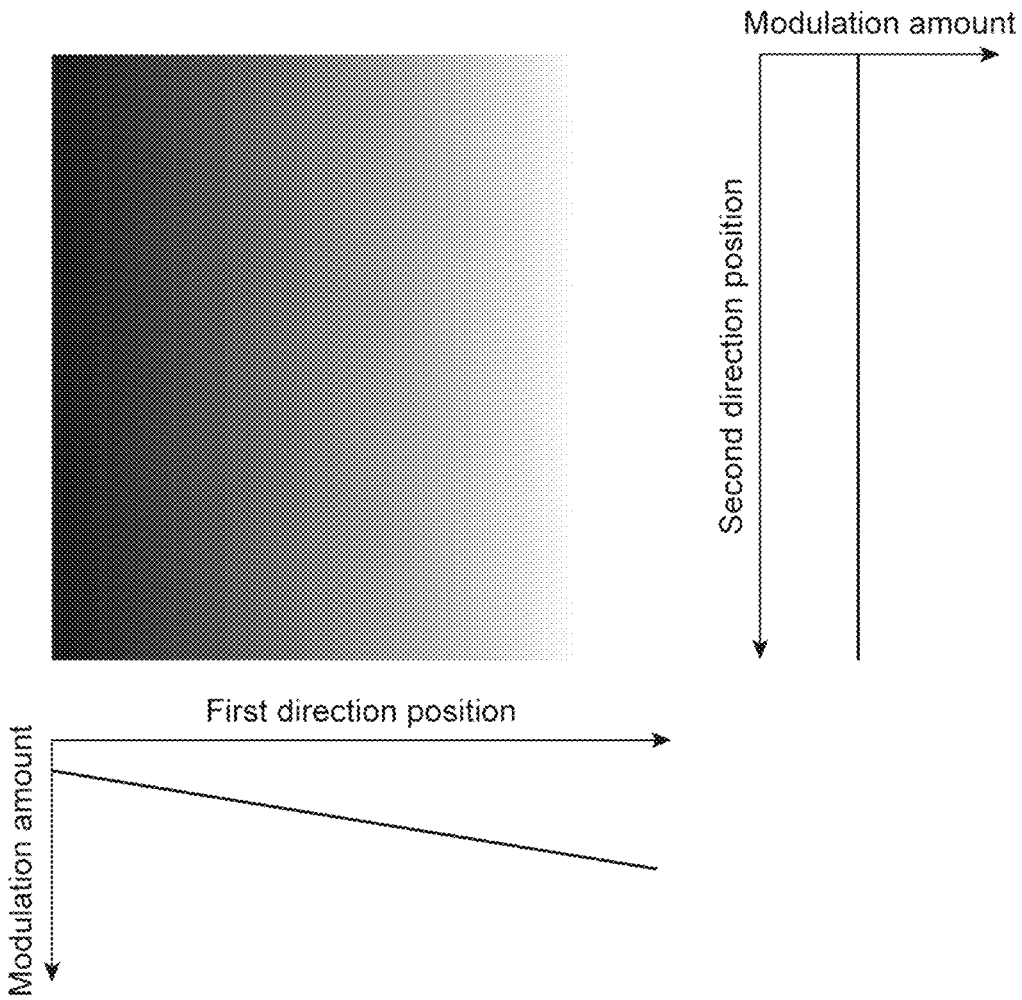
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First direction position
Modulation amount

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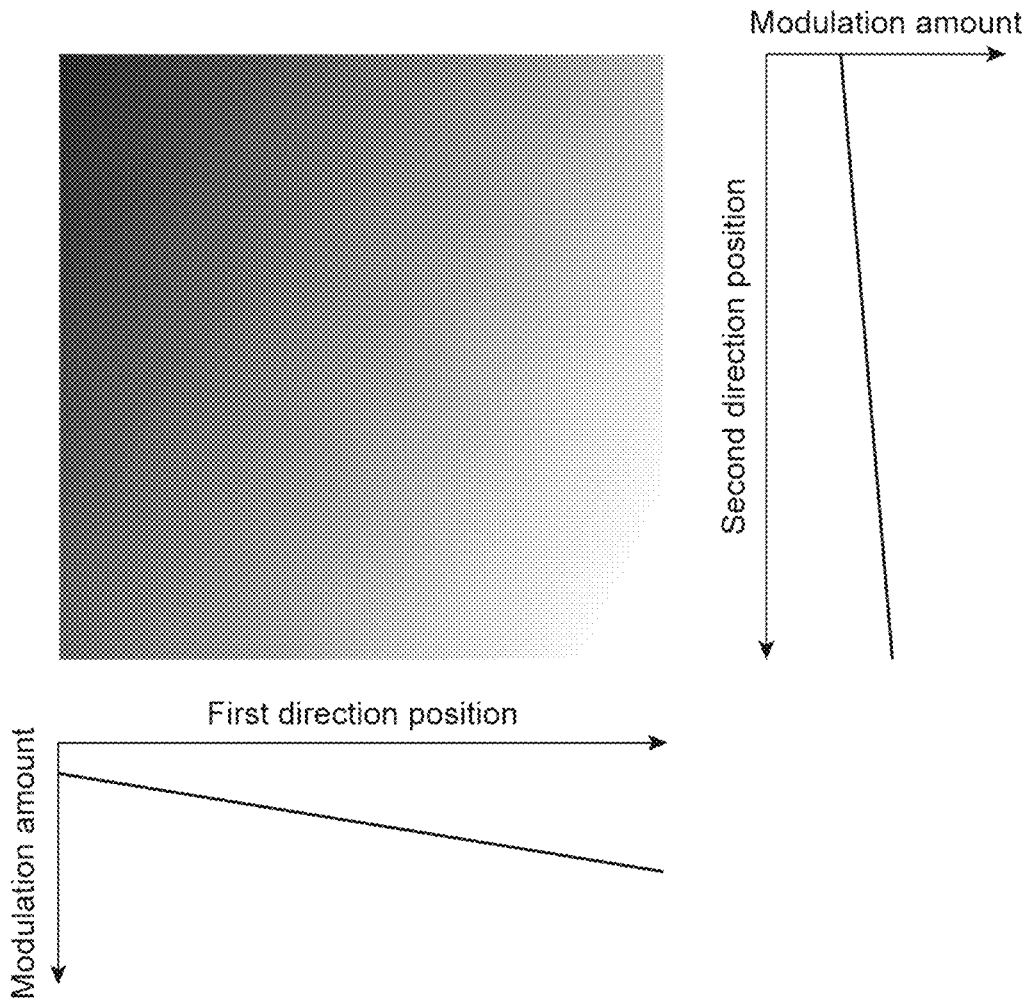
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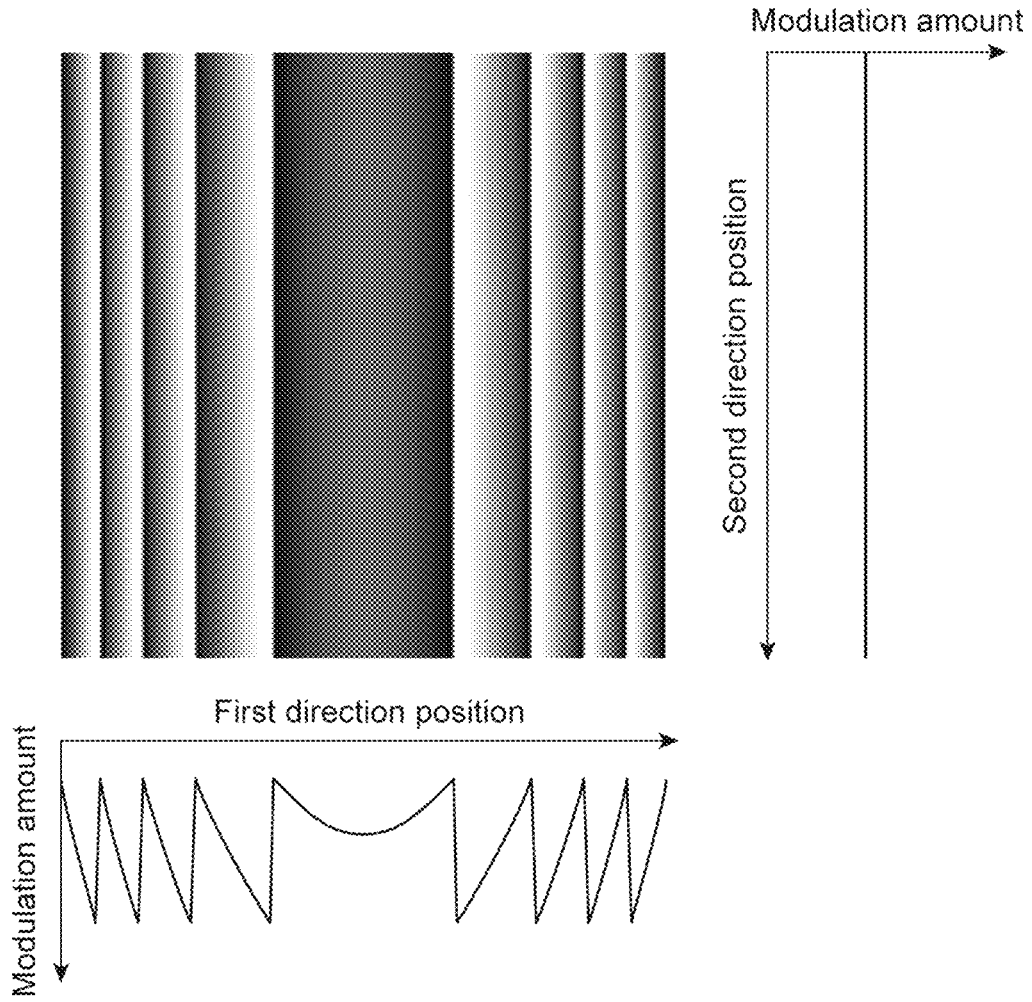
Modulation amount

Fig.35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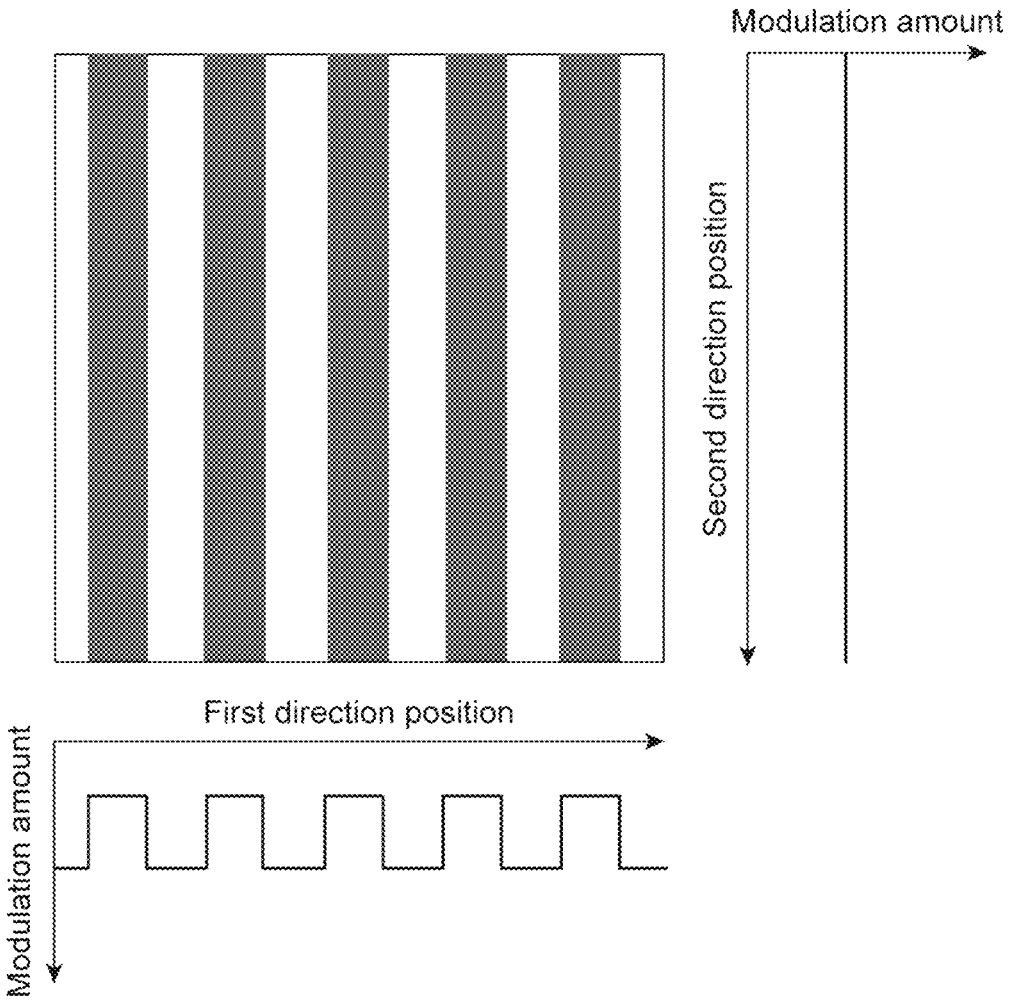
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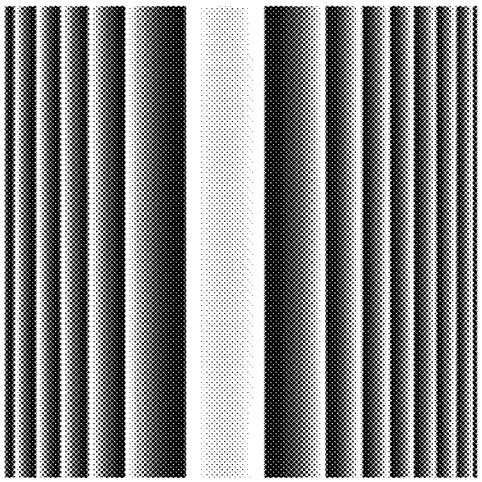
Fig.37

(a)



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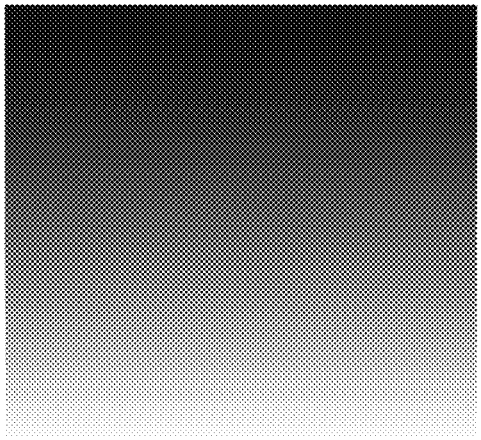

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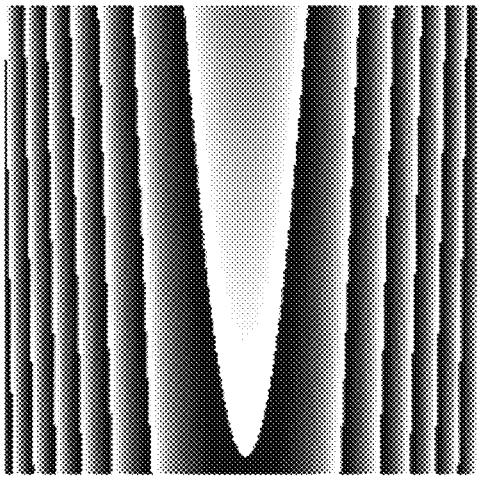


Fig.38

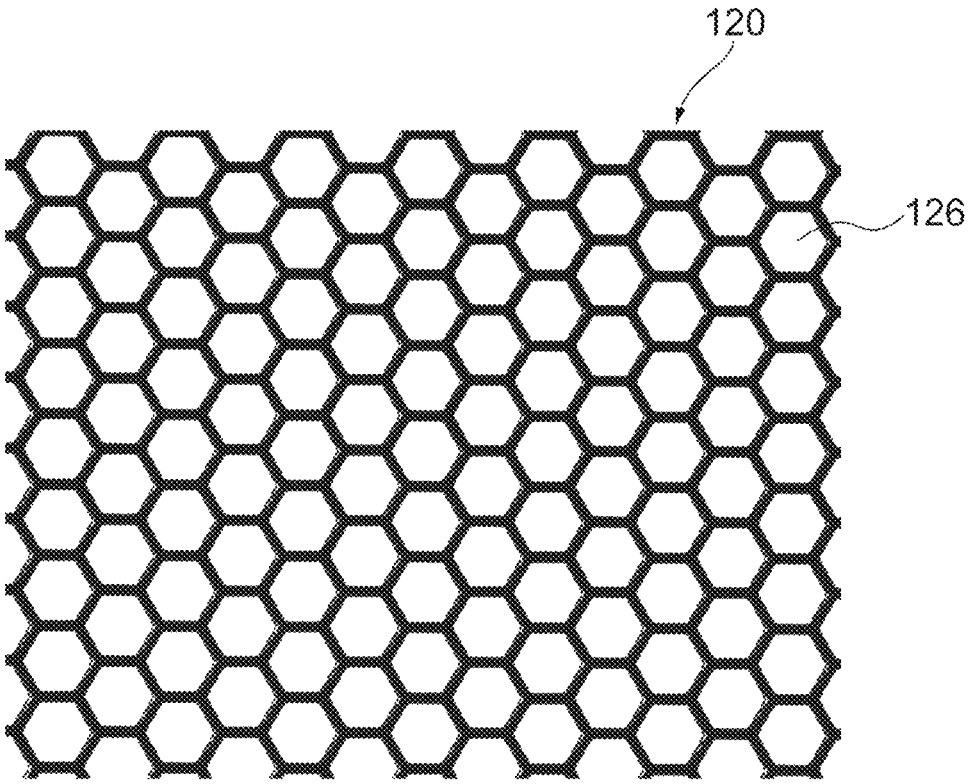
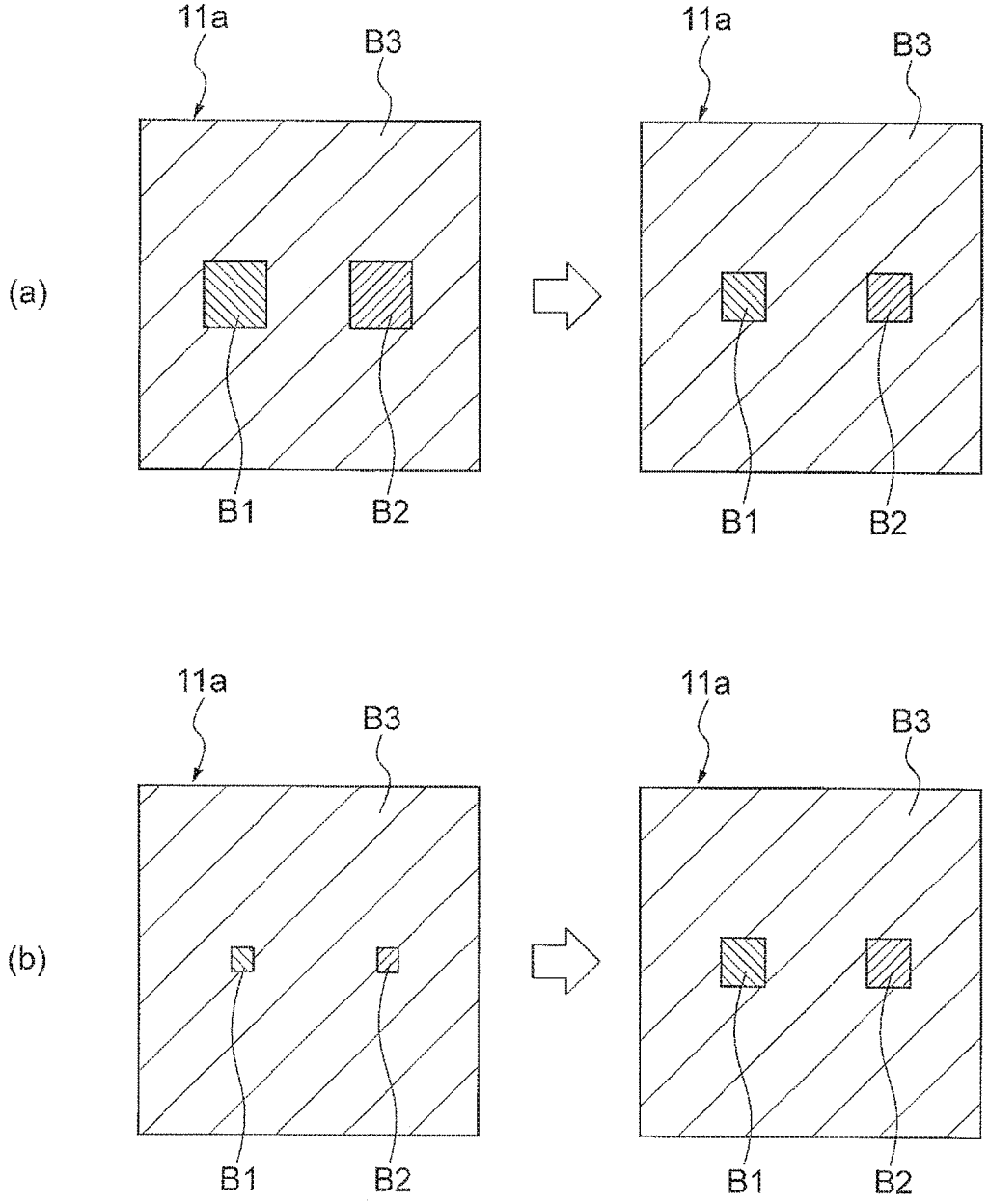


Fig.39



ANGULAR DISPLACEMENT DETECTING METHOD FOR ADAPTIVE OPTICS SYSTEM, IMAGING MAGNIFICATION DETECTING METHOD FOR ADAPTIVE OPTICS SYSTEM, AND ADAPTIVE OPTICS SYSTEM

TECHNICAL FIELD

An aspect of the present invention relates to an angular displacement detecting method for an adaptive optics system, an imaging magnification detecting method for an adaptive optics system, and an adaptive optics system.

BACKGROUND ART

In Non Patent Literatures 1 and 2, methods of adjusting an adaptive optics system according to a phase measuring method are disclosed. The phase measuring method is a method of measuring a phase distribution through a wavefront sensor after causing a spatial light modulator to display a known phase distribution and mutually associating coordinates on a modulation surface and coordinates on a detection surface by comparing a measurement result with the known phase distribution.

CITATION LIST

Non Patent Literature

[Non Patent Literature 1] Abdul Awwal, et al., "Characterization and Operation of a Liquid Crystal Adaptive Optics Phoropter," Proceedings of SPIE, Volume 5169, pp. 104-122 (2003)

[Non Patent Literature 2] Jason Porter, Hope Queener, Julianna Lin, Karen Thorn, and Abdul Awwal, "Adaptive Optics for Vision Science," Wiley Interscience, Chapter 18, pp. 496-499 (2006)

SUMMARY OF INVENTION

Technical Problem

Adaptive optics technology is technology for dynamically removing an aberration by measuring an optical aberration (wavefront distortion) using a wavefront sensor and controlling a wavefront modulation element (spatial light modulator) based on a measurement result. It is possible to improve an imaging characteristic, a degree of convergence, an SN ratio of an image, and measurement precision through the above-described adaptive optics technology. Conventionally, the adaptive optics technology was mainly used in astronomical telescopes and large laser apparatus. In recent years, the adaptive optics technology has been applied to ocular fundus cameras, scanning laser ophthalmoscopes, optical coherence tomography apparatus, laser microscopes, etc. Imaging using such adaptive optics technology enables observation at high resolution that was previously unavailable. For example, the ocular aberration is removed by applying the adaptive optics technology to an ocular fundus imaging apparatus for observing the back (ocular fundus) of the eye. For example, it is possible to clearly draw a microstructure of the ocular fundus such as a visual cell, a nerve fiber, or a capillary. The adaptive optics technology can be applied to the early diagnosis of diseases concerning circulatory system as well as ocular diseases.

In the adaptive optics system, a wavefront is controlled with precision of a light wavelength or less (for example, a sub-micro level). Therefore, angular displacement about an optical axis or a change in imaging magnification may occur between a modulation surface of a spatial light modulator and a wavefront sensor due to assembly precision of the wavefront sensor or the spatial light modulator, manufacturing errors of optical components and components for fixing the optical component, etc. When the angular displacement or the change in the imaging magnification is caused, a correspondence relation between a position of a control point in the spatial light modulator and a position of a measurement point in the wavefront sensor becomes incorrect and affects the precision of adaptive optics. Accordingly, it is desirable to easily detect the angular displacement and the imaging magnification between the modulation surface and the wavefront sensor in order to adjust a relative angle and imaging magnification between the modulation surface and the wavefront sensor. Also, for example, even when optical magnification between the modulation surface of the spatial light modulator and the wavefront sensor is variable, it is desirable to easily detect the imaging magnification between the modulation surface and the wavefront sensor.

An objective of an aspect of the present invention is to provide an angular displacement detecting method for an adaptive optics system and an adaptive optics system capable of easily detecting angular displacement about an optical axis between a modulation surface of a spatial light modulator and a wavefront sensor. Also, an objective of an aspect of the present invention is to provide an imaging magnification detecting method for an adaptive optics system and an adaptive optics system capable of easily detecting imaging magnification between a modulation surface of a spatial light modulator and a wavefront sensor.

Solution to Problem

An angular displacement detecting method for an adaptive optics system according to an aspect of the present invention is a method of calculating an amount of angular displacement between a modulation surface and a wavefront sensor in the adaptive optics system which includes a spatial light modulator configured to spatially modulate a phase of an optical image incident on the modulation surface and the wavefront sensor including a lens array having a plurality of two-dimensionally arranged lenses and an optical detection element for detecting a light intensity distribution including converging spots formed by the lens array and configured to receive the optical image after the modulation from the spatial light modulator and which compensates for wavefront distortion by controlling a phase pattern displayed in the spatial light modulator based on a wavefront shape of the optical image obtained from the light intensity distribution.

A first angular displacement detecting method includes a light intensity distribution acquiring step of acquiring the light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in first and second regions on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the first and second regions; and an angle calculating step of obtaining the amount of angular displacement between the modulation surface and the wavefront sensor based on a slope of a straight line connecting the converging spot corresponding to the first region and the converging spot corresponding to

the second region included in the light intensity distribution obtained in the light intensity distribution acquiring step.

Also, a second angular displacement detecting method includes a first light intensity distribution acquiring step of acquiring a first light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in a first region on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the first region; a second light intensity distribution acquiring step of acquiring a second light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in a second region which is a region separate from the first region on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the second region; and an angle calculating step of obtaining the amount of angular displacement between the modulation surface and the wavefront sensor based on a slope of a straight line connecting the converging spot corresponding to the first region included in the first light intensity distribution and the converging spot corresponding to the second region included in the second light intensity distribution.

The first and second angular displacement detecting methods may further include: an adjusting step of adjusting an angle around the optical image of at least one of the modulation surface and the wavefront sensor so that the amount of angular displacement calculated in the angle calculating step is reduced.

Also, in the first and second angular displacement detecting methods, the first and second regions may be regions adjacent to each other or the first and second regions may be regions separated from each other.

An imaging magnification detecting method for an adaptive optics system according to an aspect of the present invention is a method of calculating imaging magnification between a modulation surface and a wavefront sensor in the adaptive optics system which includes a spatial light modulator configured to spatially modulate a phase of an optical image incident on the modulation surface and the wavefront sensor including a lens array having a plurality of two-dimensionally arranged lenses and an optical detection element for detecting a light intensity distribution including converging spots formed by the lens array and configured to receive the optical image after the modulation from the spatial light modulator and which compensates for wavefront distortion by controlling a phase pattern displayed in the spatial light modulator based on a wavefront shape of the optical image obtained from the light intensity distribution.

A first imaging magnification detecting method includes a light intensity distribution acquiring step of acquiring the light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in first and second regions on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the first and second regions; and a magnification calculating step of obtaining the imaging magnification between the modulation surface and the wavefront sensor based on a distance between the converging spot corresponding to the first region and the converging spot corresponding to the second region included in the light intensity distribution obtained in the light intensity distribution acquiring step.

Also, a second imaging magnification detecting method includes a first light intensity distribution acquiring step of acquiring a first light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in a first region on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the first region; a second light intensity distribution acquiring step of acquiring a second light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in a second region which is a region separate from the first region on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the second region; and a magnification calculating step of obtaining the imaging magnification between the modulation surface and the wavefront sensor based on a distance between the converging spot corresponding to the first region included in the first light intensity distribution and the converging spot corresponding to the second region included in the second light intensity distribution.

The first and second imaging magnification detecting methods may further include an adjusting step of adjusting the magnification of a light guide optical system arranged between the modulation surface and the wavefront sensor so that the imaging magnification calculated in the magnification calculating step is close to predetermined imaging magnification.

Also, the first and second imaging magnification detecting methods may further include an adjusting step of adjusting an optical distance between the modulation surface and the wavefront sensor so that the imaging magnification calculated in the magnification calculating step is close to predetermined imaging magnification.

Also, the first and second imaging magnification detecting methods may further include an adjusting step of adjusting a size of a region on the modulation surface in which the phase pattern for compensating for the wavefront distortion is displayed based on the imaging magnification calculated in the magnification calculating step.

Also, in the first and second imaging magnification detecting methods, the first and second regions may be regions adjacent to each other or the first and second regions may be regions separated from each other.

Also, an adaptive optics system according to an aspect of the present invention includes: a spatial light modulator configured to spatially modulate a phase of an optical image incident on a modulation surface; a wavefront sensor including a lens array having a plurality of two-dimensionally arranged lenses and an optical detection element for detecting a light intensity distribution including converging spots formed by the lens array and configured to receive the optical image after the modulation from the spatial light modulator; and a control unit configured to compensate for wavefront distortion by controlling a phase pattern displayed in the spatial light modulator based on a wavefront shape of the optical image obtained from the light intensity distribution.

In a first adaptive optics system, the control unit acquires the light intensity distribution through the optical detection element in a state in which one of a phase pattern having

linearity in at least one direction and a spatially non-linear phase pattern is displayed in first and second regions on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the first and second regions and obtains the amount of angular displacement between the modulation surface and the wavefront sensor based on a slope of a straight line connecting the converging spot corresponding to the first region and the converging spot corresponding to the second region included in the light intensity distribution.

Also, in a second adaptive optics system, the control unit acquires a first light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in a first region on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the first region, acquires a second light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in a second region which is a region separate from the first region on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the second region, and obtains the amount of angular displacement between the modulation surface and the wavefront sensor based on a slope of a straight line connecting the converging spot corresponding to the first region included in the first light intensity distribution and the converging spot corresponding to the second region included in the second light intensity distribution.

Also, in a third adaptive optics system, the control unit acquires the light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in first and second regions on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the first and second regions, and obtains the imaging magnification between the modulation surface and the wavefront sensor based on a distance between the converging spot corresponding to the first region and the converging spot corresponding to the second region included in the light intensity distribution.

Also, in a fourth adaptive optics system, the control unit acquires a first light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in a first region on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the first region, acquires a second light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in a second region which is a region separate from the first region on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the second region, and obtains the imaging magnification between the modulation surface and the wavefront sensor based on a distance between the converging spot corresponding to the first region included in the first light intensity distribution and the converging spot corresponding to the second region included in the second light intensity distribution.

Advantageous Effects of Invention

According to an angular displacement detecting method for an adaptive optics system and an adaptive optics system according to an aspect of the present invention, it is possible to easily detect angular displacement about an optical axis between a modulation surface of a spatial light modulator and a wavefront sensor. Also, according to an imaging magnification detecting method for an adaptive optics system and an adaptive optics system according to an aspect of the present invention, it is possible to easily detect imaging magnification between a modulation surface of a spatial light modulator and a wavefront sensor.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a diagram schematically illustrating a configuration of an adaptive optics system according to an embodiment.

FIG. **2** is a cross-sectional view schematically illustrating a configuration of a wavefront sensor of an embodiment and illustrates a cross section along an optical axis of an optical image.

FIG. **3** is a view of a lens array provided in the wavefront sensor viewed in an optical axis direction of an optical image.

FIG. **4** is a view of an image sensor provided in the wavefront sensor viewed in the optical axis direction of the optical image.

FIG. **5** is a cross-sectional view schematically illustrating an LCOS type spatial light modulator as an example of a spatial light modulator of an embodiment and illustrates a cross section along the optical axis of the optical image.

FIG. **6** is a front view of a modulation surface of the spatial light modulator.

FIG. **7** is a conceptual view illustrating the principle of an adjustment method in an embodiment.

FIG. **8** is a diagram conceptually illustrating a special phase pattern displayed on the modulation surface.

FIG. **9** is a diagram conceptually illustrating light intensity distribution data (Shack-Hartmann-Gram) detected by the image sensor of the wavefront sensor.

FIG. **10** is a diagram conceptually illustrating a relative relation between the modulation surface and the lens array.

FIG. **11** is a diagram illustrating a state of a position change in a converging spot of the light intensity distribution data due to angular displacement between the modulation surface and the wavefront sensor.

FIG. **12** is a diagram illustrating a random distribution in which a distribution of magnitudes of phases is irregular as an example of a spatially non-linear phase pattern.

FIG. **13** is a diagram illustrating a defocus distribution which increases a diameter of a converging spot as an example of the spatially non-linear phase pattern.

FIG. **14** is a diagram illustrating a distribution which causes a large spherical aberration in an optical image as an example of the spatially non-linear phase pattern.

FIG. **15** is a diagram illustrating a distribution which causes an aberration including a high-order aberration in the optical image as an example of the spatially non-linear phase pattern.

FIG. **16** illustrates an example of a phase pattern in which a common phase distribution (for example, a defocus distribution) is arranged for every two or more regions.

FIG. **17** illustrates an example of a phase pattern in which different phase distributions (for example, phase distributions in which an aberration including a high-order aberration is caused) are arranged for every two or more regions.

FIG. **18** is a diagram illustrating a phase distribution in which phase values are substantially uniform across the entire surface of the modulation surface as an example of a phase pattern having linearity in at least one direction.

FIG. **19** is a block diagram illustrating an example of an internal configuration of a control unit.

FIG. **20** is a flowchart illustrating an angular displacement detecting method and an operation of an adaptive optics system according to a first embodiment.

FIG. **21** is a flowchart illustrating an angular displacement detecting method and an operation of a control unit according to a second embodiment.

FIG. **22** is a diagram conceptually illustrating a phase pattern of a first modified example.

FIG. **23** is a diagram conceptually illustrating another phase pattern of the first modified example.

FIG. **24** is a diagram conceptually illustrating a special phase pattern for detecting an amount of angular displacement to be displayed on a modulation surface in a third embodiment.

FIG. **25**(*a*) is a diagram conceptually illustrating a relative relation between each region on the modulation surface and a lens array and illustrates the case in which there is no angular displacement between the modulation surface and the wavefront sensor and the case in which there is no positional displacement between the modulation surface and the wavefront sensor. FIG. **25**(*b*) is a diagram illustrating light intensity distribution data in the case illustrated in FIG. **25**(*a*).

FIG. **26**(*a*) is a diagram conceptually illustrating a relative relation between each region on the modulation surface and a lens array and illustrates the case in which angular displacement (displacement amount θ) occurs between the modulation surface and the wavefront sensor.

FIG. **26**(*b*) is a diagram illustrating light intensity distribution data in the case illustrated in FIG. **26**(*a*).

FIG. **27**(*a*) is a diagram conceptually illustrating a relative relation between each region on the modulation surface and a lens array and illustrates the case in which positional displacement occurs within a surface perpendicular to an optical axis of the optical image in addition to angular displacement (displacement amount θ) between the modulation surface and the wavefront sensor. FIG. **27**(*b*) is a diagram illustrating light intensity distribution data in the case illustrated in FIG. **27**(*a*).

FIG. **28** is a flowchart illustrating an angular displacement detecting method and an operation of a control unit according to a third embodiment.

FIG. **29** is a flowchart illustrating an imaging magnification detecting method and an operation of a control unit according to a fourth embodiment.

FIG. **30** is a flowchart illustrating an imaging magnification detecting method and an operation of a control unit according to a fifth embodiment.

FIG. **31** is a diagram illustrating an example of an arrangement of first and second regions.

FIG. **32** is a diagram illustrating an example of an arrangement of first and second regions.

FIG. **33** is a diagram illustrating a phase distribution in which phase values are inclined in a first direction (for example, a row direction) and phase values are substantially uniform in a second direction (for example, a column direction) intersecting the first direction.

FIG. **34** is a diagram illustrating a phase distribution in which phase values are inclined in both the first direction (for example, the row direction) and the second direction (for example, the column direction).

FIG. **35** is a diagram illustrating a phase distribution having a cylindrical lens effect in the first direction and in which phase values are substantially uniform in the second direction as an example of a phase pattern having linearity in at least one direction.

FIG. **36** is a diagram illustrating a phase distribution constituting a diffraction grating in the first direction and in which phase values are substantially uniform in the second direction as an example of a phase pattern having linearity in at least one direction.

FIG. **37** is a diagram illustrating an example of a composite pattern obtained by superimposition.

FIG. **38** is a diagram illustrating a modified example of a lens array.

FIG. **39** is a diagram illustrating an example of the case in which sizes of first and second regions are configured to be variable.

DESCRIPTION OF EMBODIMENTS

Hereinafter, embodiments of an angular displacement detecting method for an adaptive optics system, an imaging magnification detecting method for an adaptive optics system, and an adaptive optics system according to an aspect of the present invention will be described with reference to the accompanying drawings. Also, the same elements are assigned the same reference signs in the description of the drawings and redundant description thereof will be omitted. Also, in the following description, it is assumed that a "phase distribution" indicates two-dimensionally distributed phase values, a "phase pattern" indicates a pattern obtained by coding the phase distribution (two-dimensional phase values) based on a certain standard, and a "phase profile" indicates a distribution of phase values in a certain direction (line) in the phase distribution.

(First Embodiment)

FIG. **1** is a diagram schematically illustrating a configuration of an adaptive optics system **10** according to this embodiment. The adaptive optics system **10**, for example, is embedded in an ophthalmologic inspection apparatus, a laser processing apparatus, a microscope apparatus, an adaptive optics apparatus, or the like. This adaptive optics system **10** includes a spatial light modulator (SLM) **11**, a wavefront sensor **12**, a control unit **13**, a beam splitter **14**, relay lenses **15** and **16**, and a control circuit unit **17**.

The spatial light modulator **11** receives an optical image La by a modulation surface **11***a* which displays a phase pattern and modulates a wavefront shape of the optical image La to output the modulated wavefront shape. The optical image La incident on the spatial light modulator **11**, for example, is light emitted from a laser light source or a super luminescent diode (SLD) or reflected light, scattered light, fluorescent light, or the like generated from an observation object irradiated with light. The wavefront sensor **12** provides the control unit **13** with data S1 including information about the wavefront shape of the optical image La reaching from the spatial light modulator **11** (typically indicating distortion of a wavefront, that is, displacement of a wavefront from a reference wavefront, shown due to an aberration of an optical system). The control unit **13** gener-

ates a control signal S2 for displaying a phase pattern suitable for the spatial light modulator **11** based on the data S1 obtained from the wavefront sensor **12**. In an example, the control unit **13** includes an input unit configured to input the data S1 from the wavefront sensor **12**, an aberration calculation unit configured to calculate an aberration from the data S1, a phase pattern calculation unit configured to calculate a phase pattern to be displayed in the spatial light modulator **11**, and a signal generation unit configured to generate the control signal S2 according to the calculated phase pattern. The control circuit unit **17** receives the control signal S2 from the control unit **13** and applies a voltage V1 based on the control signal S2 to a plurality of electrodes of the spatial light modulator **11**.

The beam splitter **14** is arranged between the wavefront sensor **12** and the spatial light modulator **11** and branches the optical image La. The beam splitter **14** may be a beam splitter of a polarization direction independent type, a polarization direction dependent type, or a wavelength dependent type (dichroic mirror). One optical image La branched by the beam splitter **14**, for example, is sent to an optical detection element **18** such as a CCD, a photomultiplier tube, or an avalanche photodiode. The optical detection element **18**, for example, is embedded in a scanning laser ophthalmoscope (SLO), an optical coherence tomography (OCT) camera, an ocular fundus camera, a microscope, a telescope, or the like. In addition, the other optical image La branched by the beam splitter **14** is incident on the wavefront sensor **12**.

The relay lenses **15** and **16** are arranged side by side in an optical axis direction between the spatial light modulator **11** and the wavefront sensor **12**. The spatial light modulator **11** and the wavefront sensor **12** are maintained in a mutually optical conjugate relation by the relay lenses **15** and **16**. Also, an optical imaging lens and/or a polarization mirror, etc. may be further arranged between the spatial light modulator **11** and the wavefront sensor **12**.

FIG. **2** is a cross-sectional view schematically illustrating a configuration of the wavefront sensor **12** of this embodiment and illustrates a cross section along the optical axis of the optical image La. FIG. **3** is a view of a lens array **120** provided in the wavefront sensor **12** viewed in the optical axis direction of the optical image La. FIG. **4** is a view of an image sensor (optical detection element) **122** provided in the wavefront sensor **12** viewed in the optical axis direction of the optical image La.

Although the wavefront sensor **12** may be of an interference type or a non-interference type, the non-interference type Shack-Hartmann wavefront sensor having the lens array **120** and the image sensor **122** is used as the wavefront sensor **12** in this embodiment. When the non-interference type wavefront sensor is used, there is an advantage in that vibration insensitivity is excellent and a configuration of the wavefront sensor and a process of calculating measurement data can be simpler than when the interference type wavefront sensor is used.

As illustrated in FIG. **3**, the lens array **120** has N (N is an integer greater than or equal to 4) lenses **124**. The N lenses **124**, for example, are arranged in a two-dimensional lattice shape of Na rows and Nb columns (Na and Nb are integers greater than or equal to 2).

Also, the image sensor **122** illustrated in FIG. **2** has a light receiving surface **122***a* at a position overlapping a back focal plane of the N lenses **124** constituting the lens array **120** and detects a light intensity distribution including N converging spots P formed by the N lenses **124**. As illustrated in FIG. **4**, the image sensor **122** is configured to include a plurality of pixels **122***b* arranged in a two-dimensional lattice shape of Ma rows and Mb columns (Ma and Mb are integers greater than or equal to 2). An array pitch of the pixels **122***b* of the image sensor **122** is configured to be sufficiently less than an array pitch of the lenses **124** so that a magnitude of displacement of a converging image position from the reference position can be detected with high precision.

In the control unit **13** to be described below, a wavefront shape (a distribution of phase gradients) of the optical image La is measured based on a light intensity distribution detected by the image sensor **122**. That is, a magnitude of displacement between the position of the converging spot P by the lens **124** and the reference position is proportional to a slope of a local wavefront of the optical image La incident on the lens **124**. Accordingly, it is possible to calculate the magnitude of the positional displacement of the converging spot P from the reference position for each lens **124** and measure a wavefront shape of the optical image La based on the positional displacement of the converging spot P.

It is possible to designate a position at which an optical axis of each of the plurality of lenses **124** intersects the light receiving surface **122***a* of the image sensor **122** as the reference position to be used to calculate the magnitude of the displacement of the converging image position. This position is easily obtained through center-of-gravity calculation using a converging image obtained by causing parallel plane waves to be perpendicularly incident on each lens **124**.

The spatial light modulator **11** is an element which receives the optical image La from a light source or an observation object and modulates a wavefront of the optical image La to output the modulated wavefront. Specifically, the spatial light modulator **11** has a plurality of pixels (control points) arranged in a two-dimensional lattice shape and changes a modulation amount (for example, a phase modulation amount) of each pixel according to the control signal S2 provided from the control unit **13**. The spatial light modulator **11**, for example, includes a liquid crystal on silicon spatial light modulator (LCOS-SLM), a programmable phase modulator (PPM), a liquid crystal display (LCD), micro electro mechanical systems (MEMS), or an electrical address type spatial light modulator formed by coupling an LCD element and an optical address type liquid-crystal spatial light modulator. Also, although the reflection type spatial light modulator **11** is illustrated in FIG. **1**, the spatial light modulator **11** may be of a transmission type.

FIG. **5** is a cross-sectional view schematically illustrating an LCOS type spatial light modulator as an example of the spatial light modulator **11** of this embodiment and illustrates a cross section along the optical axis of the optical image La. This spatial light modulator **11** includes a transparent substrate ill, a silicon substrate **112**, a plurality of pixel electrodes **113**, a liquid crystal unit (modulation unit) **114**, a transparent electrode **115**, oriented films **116***a* and **116***b*, a dielectric mirror **117**, and a spacer **118**.

The transparent substrate **111** is formed of a material which transmits the optical image La and arranged along a main surface of the silicon substrate **112**. The plurality of pixel electrodes **113** are arranged in a two-dimensional lattice shape on the main surface of the silicon substrate **112** and constitute pixels of the spatial light modulator **11**. The transparent electrode **115** is arranged on the surface of the transparent substrate **111** opposite to the plurality of pixel electrodes **113**. The liquid crystal unit **114** is arranged between the plurality of pixel electrodes **113** and the transparent electrode **115**. The oriented film **116***a* is arranged between the liquid crystal unit **114** and the transparent

electrode **115** and the oriented film **116***b* is arranged between the liquid crystal unit **114** and the plurality of pixel electrodes **113**. The dielectric mirror **117** is arranged between the oriented film **116***b* and the plurality of pixel electrodes **113**. The dielectric mirror **117** reflects the optical image La incident from the transparent substrate **111** and transmitted through the liquid crystal unit **114** and causes the optical image La to be re-emitted from the transparent substrate **111**.

Also, the spatial light modulator **11** further includes a pixel electrode circuit (active matrix drive circuit) **119** configured to control a voltage to be applied between the plurality of pixel electrodes **113** and the transparent electrode **115**. When the voltage is applied from the pixel electrode circuit **119** to any pixel electrode **113**, a refractive index of the liquid crystal unit **114** on the pixel electrode **113** changes according to a magnitude of an electric field generated between the pixel electrode **113** and the transparent electrode **115**. Accordingly, an optical path length of the optical image La transmitted through a relevant part of the liquid crystal unit **114** changes and consequently a phase of the optical image La changes. By applying voltages of various magnitudes to the plurality of pixel electrodes **113**, it is possible to electrically write a spatial distribution of a phase adjustment amount and implement various wavefront shapes if necessary.

FIG. **6** is a front view of a modulation surface **11***a* of the spatial light modulator **11**. As illustrated in FIG. **6**, the modulation surface **11***a* is configured to include a plurality of pixels **11***b* arranged in a two-dimensional lattice shape of Pa rows and Pb columns (Pa and Pb are integers greater than or equal to 2). Also, each of the plurality of pixels **11***b* is constituted of one of the plurality of pixel electrodes **113**.

Description will now return to FIG. **1**. In this adaptive optics system **10**, the optical image La from a light source or an observation object (not illustrated) is first incident on the spatial light modulator **11** as substantially parallel light. The optical image La modulated by the spatial light modulator **11** is incident on the beam splitter **14** via the relay lenses **15** and **16** and is branched into two optical images. One optical image La after the branching is incident on the wavefront sensor **12**. The data S**1** including the wavefront shape (for example, a phase distribution) of the optical image La is generated in the wavefront sensor **12** and the data S**1** is provided to the control unit **13**. The control unit **13** calculates the wavefront shape (phase distribution) of the optical image La if necessary based on the data S**1** from the wavefront sensor **12** and outputs the control signal S**2** including the phase pattern for appropriately compensating for wavefront distortion of the optical image La to the spatial light modulator **11**. Thereafter, the non-distortion optical image La compensated for by the spatial light modulator **11** is branched by the beam splitter **14** and is incident on the optical detection element **18** via an optical system (not illustrated) and captured.

Here, a coordinate system in the modulation surface **11***a* of the spatial light modulator **11** and the detection surface of the wavefront sensor **12** is set as follows. That is, two directions parallel to the modulation surface **11***a* of the spatial light modulator **11** and orthogonal to each other are designated as an x-axis direction and a y-axis direction in the modulation surface **11***a* and two directions parallel to the detection surface of the wavefront sensor **12** and orthogonal to each other are designated as an x-axis direction and a y-axis direction in the detection surface. However, the x axis in the modulation surface **11***a* of the spatial light modulator **11** and the x axis in the detection surface of the wavefront sensor **12** are directed to be opposite to each other and the y axis in the modulation surface **11***a* of the spatial light modulator **11** and the y axis in the detection surface of the wavefront sensor **12** are directed to be opposite to each other. Also, the center of the modulation surface **11***a* of the spatial light modulator **11** is designated as the origin of the coordinate system in the modulation surface **11***a* and a point obtained by mapping the center of the modulation surface **11***a* to the detection surface of the wavefront sensor **12** is designated as the origin of the coordinate system in the detection surface.

At this time, the phase of the wavefront at a position (Xs, Ys) on the modulation surface **11***a* of the spatial light modulator **11** is mapped one-to-one to the phase of the wavefront at a position (Xc, Yc) on the detection surface of the wavefront sensor **12**, and a relation between them is expressed by the following Formulas (1) when there is no angular displacement about the optical axis between the modulation surface **11***a* and the detection surface.

[Math 1]

$$Xs = \frac{Xc}{M} \qquad (1)$$
$$Ys = \frac{Yc}{M}$$

Here, M denotes magnifications of the relay lenses **15** and **16**. Also, the magnification M included in Formulas (1) is known in many cases.

However, the angular displacement about the optical axis may occur between the modulation surface **11***a* and the detection surface of the wavefront sensor **12** due to vibration at the time of transportation or in an installation place or deformation or the like of a member for holding the wavefront sensor or the spatial light modulator by heat. In an angular displacement adjusting method for the adaptive optics system according to this embodiment, a special phase pattern for adjustment is displayed in the spatial light modulator **11** and a feature caused by the phase pattern is detected in the wavefront sensor **12**, so that an amount of angular displacement between the wavefront sensor **12** and the modulation surface **11***a* is acquired. If necessary, angular adjustment between the modulation surface **11***a* and the wavefront sensor **12** is performed based on the amount of angular displacement.

Hereinafter, a method of detecting the amount of angular displacement between the modulation surface **11***a* and the wavefront sensor **12** will be described in detail. Also, the detecting method is stored as a program inside a storage region **13***a* of the control unit **13** illustrated in FIG. **1** and the control unit **13** performs the detecting method by reading the program.

FIG. **7** is a conceptual view illustrating the principle of the detecting method according to this embodiment. In FIG. **7**, the relay lenses **15** and **16**, a wavefront W**1** of an optical image incident on the modulation surface **11***a*, a wavefront W**2** of the optical image emitted from the modulation surface **11***a*, and a wavefront W**3** of the optical image incident on the wavefront sensor **12** are illustrated in addition to the modulation surface **11***a* of the spatial light modulator **11** and the wavefront sensor **12** (the lens array **120** and the image sensor **122**). The wavefront W**2** obtained by applying a wavefront according to the phase pattern displayed in the spatial light modulator **11** to the incident wavefront W**1** is emitted from the spatial light modulator **11**.

The wavefront W3 via a conjugate optical system including the relay lenses **15** and **16** is incident on the wavefront sensor **12**. In addition, the optical image La emitted from the region on the modulation surface **11***a* corresponding to one lens **124** and reaching the lens **124** is illustrated in FIG. **7**.

Here, FIG. **8** is a diagram conceptually illustrating a special phase pattern displayed on the modulation surface **11***a*. As illustrated in FIG. **8**, a first phase pattern having linearity in at least one direction is displayed in a first region B1 on the modulation surface **11***a* having a size corresponding to one lens **124** and a second region B2 on the modulation surface **11***a* separated from the first region B1 and having a size corresponding to another lens **124**. The first phase pattern, for example, is implemented to include a substantially uniform phase distribution, a phase distribution inclined in at least one direction, or the like. Alternatively, the first phase pattern is implemented to include a phase distribution having a cylindrical lens effect in a certain first direction and substantially uniform in a second direction intersecting the first direction or a phase distribution constituting a diffraction grating in the first direction and substantially uniform in the second direction intersecting (for example, orthogonal to) the first direction.

Also, simultaneously, a spatially non-linear second phase pattern (for example, a random distribution in which a distribution of magnitudes of phases is irregular, a defocus distribution which increases a diameter of a converging spot, or the like) is displayed in a region B3 surrounding the first region B1 and the second region B2 on the modulation surface **11***a*. Then, a wavefront of a part corresponding to the region B3 in the emission wavefront W2 is disturbed (part A1 of FIG. **7**). The disturbance of the wavefront occurs even in a part incident on the lens **124** corresponding to the region B3 in the incident wavefront W3 for the wavefront sensor **12** (part A2 of FIG. **7**). Thereby, the converging spot P formed by the lens **124** diverges and the converging spot P is not formed, the maximum luminance of the spot is reduced, or a spot diameter is widened. That is, only the converging spot corresponding to the region B3 with degraded clarity can be formed.

On the other hand, the wavefront is incident on the lens **124** without being disturbed in at least one direction according to a first phase pattern having linearity in the at least one direction in parts (parts A3 and A4 of FIG. **7**) corresponding to the first and second regions B1 and B2 in the wavefronts W2 and W3. Accordingly, the converging spot P is clearly formed by the lens **124**.

FIG. **9** is a diagram conceptually illustrating light intensity distribution data (Shack-Hartmann-Gram) detected by the image sensor **122** of the wavefront sensor **12**. FIG. **9**(*a*) illustrates light intensity distribution data D1 of the case in which a phase pattern having linearity in at least one direction is displayed in the regions B1 and B2 and the spatially non-linear phase pattern is displayed in the region B3. FIG. **9**(*b*) illustrates light intensity distribution data D2 of the case in which a phase pattern having linearity in all regions is displayed for comparison.

When the phase pattern having the linearity in all the regions is displayed as illustrated in FIG. **9**(*b*), N converging spots P corresponding to N lenses **124** are included in the light intensity distribution data. On the other hand, when the phase pattern having the linearity in the at least one direction is displayed in the regions B1 and B2 and the spatially non-linear phase pattern is displayed in the region B3 as illustrated in FIG. **9**(*a*), two converging spots P corresponding to the regions B1 and B2 are included in the light intensity distribution data, but the converging spot corresponding to the region B3 is not formed, the maximum luminance of the spot is reduced, or the spot diameter is widened. That is, only the converging spot corresponding to the region B3 with degraded clarity is formed.

Here, FIG. **10** is a diagram conceptually illustrating a relative relation between the modulation surface **11***a* and the lens array **120**. FIG. **10**(*a*) illustrates the case in which there is no angular displacement between the modulation surface **11***a* and the wavefront sensor **12**, that is, the case in which an arrangement direction of the modulation surface **11***a* and an arrangement direction of the lens **124** (indicated by a broken line in the drawing) are aligned. In this case, N regions **11***c* (indicated by a bold line in the drawing) in the modulation surface **11***a* correspond to the N lenses **124**. Also, the plurality of pixels **11***b* are included in each region **11***c*.

In contrast, when angular displacement occurs between the modulation surface **11***a* and the wavefront sensor **12**, displacement occurs at relative positions between the N regions **11***c* of the modulation surface **11***a* and the N lenses **124** as illustrated in FIG. **10**(*b*). The optical image La from the region **11***c* separated from the center of the angular displacement is incident on another lens **124** different from the lens **124** corresponding to the region **11***c*.

The light intensity distribution data D1 illustrated in FIG. **9**(*a*) changes as follows due to such angular displacement. FIG. **11** is a diagram illustrating a state of a position change in a converging spot P of the light intensity distribution data D1 due to angular displacement between the modulation surface **11***a* and the wavefront sensor **12**. When there is no angular displacement between the modulation surface **11***a* and the wavefront sensor **12**, the two converging spots P1 corresponding to the regions B1 and B2 are formed at predetermined positions. However, when the angular displacement occurs between the modulation surface **11***a* and the wavefront sensor **12**, the two converging spots P2 corresponding to the regions B1 and B2 are formed at different positions from the above-described converging spots P1 as illustrated in FIG. **11**.

A relative positional relation between two converging spots P2 is uniquely defined according to an amount of angular displacement between the modulation surface **11***a* and the wavefront sensor **12**. Specifically, an angle θ formed by a line segment L1 connecting the two converging spots P1 and a line segment L2 connecting the two converging spots P2 matches the amount of angular displacement between the modulation surface **11***a* and the wavefront sensor **12**. Therefore, it is possible to know the amount θ of angular displacement between the modulation surface **11***a* and the wavefront sensor **12** by investigating the relative positional relation between the converging spot P corresponding to the region B1 and the converging spot P corresponding to the region B2 included in the light intensity distribution data D1. Also, the angular displacement amount θ is calculated according to the following Formula (2).

[Math 2]

$$\theta = \arccos\left(\frac{\vec{a}\cdot\vec{b}}{|\vec{a}||\vec{b}|}\right) \tag{2}$$

Here, $\vec{a}$ and $\vec{b}$ denote direction vectors of the line segments L1 and L2. In addition, the angular displacement amount θ may be calculated by substituting a direction vector of a line

segment connecting the centers of the regions B1 and B2 into the direction vector $\vec{a}$ of the line segment L1.

Here, an example of a "spatially non-linear second phase pattern" displayed in the region B3 of FIG. **8** is shown. FIGS. **12** to **15** are diagrams illustrating examples of such a phase pattern, wherein a magnitude of a phase is shown according to light and shade, a phase of a darkest part is 0 (rad), and a phase of a brightest part is 2π (rad).

FIG. **12** illustrates a random distribution in which a distribution of magnitudes of phases is irregular. Also, an example in which a graph of a phase modulation amount at one position of each of row and column directions is also illustrated in FIG. **12**. When this phase pattern is displayed in the region B3, the optical image La of a relevant part diverges and a clear converging spot P is not formed. FIG. **13** illustrates a defocus distribution which increases a diameter of a converging spot P. Even in FIG. **13**, an example of a graph of a phase modulation amount at one position of each of row and column directions is illustrated. When such a phase pattern is displayed in the region B3, a clear converging spot P is not formed because the optical image La of the relevant part is conversely widened without converging. FIG. **14** illustrates a distribution which causes a large spherical aberration in the optical image La. FIG. **15** illustrates a distribution which causes an aberration including a large high-order aberration in the optical image La. Even when the phase pattern illustrated in FIG. **14** or **15** is displayed in the region B3, the clear converging spot P is not formed. The spatially non-linear second phase pattern may include at least one of the above-described distributions or may include a composite pattern in which at least one of the above-described distributions and a linear phase pattern are superimposed.

Also, the non-linear second phase pattern displayed in the region B3 may include a common phase distribution for every two or more regions formed by dividing the region B3 and may include different phase distributions for every two or more regions formed by dividing the region B3. FIG. **16** illustrates an example of a phase pattern in which a common phase distribution (for example, a defocus distribution) is arranged for every two or more regions formed by dividing the region B3. Also, FIG. **17** illustrates an example of a phase pattern in which different phase distributions (for example, phase distributions which cause an aberration including a high-order aberration) are arranged for every two or more regions formed by dividing the region B3.

A "first phase pattern having linearity in at least one direction" displayed in the regions B1 and B2 of FIG. **8**, for example, is implemented by a phase distribution in which phase values are substantially uniform across the entire surface of the modulation surface **11***a*. FIG. **18** is a diagram illustrating such a phase pattern, wherein the magnitude of the phase is indicated by light and shade as in FIGS. **12** to **17**. Because the wavefront of the optical image La of the relevant part is flat when the phase pattern as illustrated in FIG. **18** is displayed in the regions B1 and B2, the clear converging spot P is formed by the lens **124**.

FIG. **19** is a block diagram illustrating an example of an internal configuration of the control unit **13** of this embodiment. The control unit **13** can be configured to include a pattern creation unit **13***b* and a calculation processing unit **13***c*. Also, the pattern creation unit **13***b* and the calculation processing unit **13***c* are stored as a program inside the storage region **13***a* of the control unit **13** illustrated in FIG. **1** and implemented by the control unit **13** reading and executing the program.

The pattern creation unit **13***b* creates a special phase pattern for detecting an amount of angular displacement between the modulation surface **11***a* and the wavefront sensor **12**, that is, a phase pattern including the regions B1 to B3. Also, the phase pattern is sent as a control signal S2 from the pattern creation unit **13***b* to the control circuit unit **17**.

Here, a special phase pattern PA for detecting the angular displacement amount, for example, is expressed by the following Formula (3).

[Math 3]

$$P_A(n,m)=\begin{cases} a & (n,m)\subset ROI \\ rand() & (n,m)\not\subset ROI \end{cases} \tag{3}$$

Here, a denotes a certain constant and is an example of a first phase pattern having linearity in at least one direction. Also, rand( ) denotes a random function and is an example of a spatially non-linear second phase pattern. (n, m) denotes coordinates in units of pixels on the modulation surface **11***a*. ROI is defined as a reference sign denoting the regions B1 and B2.

As described above, each of the regions B1 and B2 in this embodiment has a size corresponding to one lens **124**. When the plurality of lenses **124** are arranged in a two-dimensional lattice shape as illustrated in FIG. **3** in the lens array **120**, shapes of the regions B1 and B2 become squares. Accordingly, the above Formula (3) can be modified as in the following Formula (4).

[Math 4]

$$P_A(n,m)=\begin{cases} a & |n-xc_1|\le \frac{w}{2},\ |m-yc_1|\le \frac{w}{2} \\ a' & |n-xc_2|\le \frac{w}{2},\ |m-yc_2|\le \frac{w}{2} \\ rand() & (n,m)\not\subset ROI \end{cases} \tag{4}$$

Here, (xc_1, yc_1) is center coordinates of the region B1, (xc_2, yc_2) is center coordinates of the region B2, w is the number of pixels of one side of the region B1 or B2, and a' is the same constant as the constant a or a different constant from the constant a. Also, assuming that an array pitch of the pixels **11***b* in the modulation surface **11***a* is denoted by slmPITCH, an array pitch of the lenses **124** in the lens array **120** is denoted by mlaPITCH, and imaging magnification of an optical system between the modulation surface **11***a* and the lens surface of the lens array **120** is denoted by M, the number of pixels w of one side of the region B1 or B2 is expressed by the following Formula (5).

[Math 5]

$$w=\frac{1}{M}\times\frac{mlaPITCH}{slmPITCH} \tag{5}$$

In other words, a width (=w×slmPITCH) of the region B1 or B2 in an array direction of the plurality of lenses **124** is (1/M) times the array pitch mlaPITCH of the plurality of lenses **124**.

When the above-described phase pattern P_A is displayed on the modulation surface **11***a*, the calculation processing unit **13***c* acquires the light intensity distribution data **S1** output from the wavefront sensor **12**. The calculation processing unit **13***c* calculates a center of gravity position of each converging spot P included in the light intensity distribution data **S1** according to an algorithm that will be described below. The calculation processing unit **13***c* calculates an amount of angular displacement between the modulation surface **11***a* and the wavefront sensor **12** based on the center of gravity position of the converging spot P corresponding to the region B**1** and the center of gravity position of the converging spot P corresponding to the region B**2**.

An operation of the adaptive optics system **10** including detection of the amount of angular displacement between the modulation surface **11***a* and the wavefront sensor **12** described above will be described with reference to FIG. **20**. FIG. **20** is a flowchart illustrating the operation and angular displacement detecting method of the adaptive optics system **10** of this embodiment. Also, the angular displacement detecting method is stored as a program for the adaptive optics system inside the storage region **13***a* of the control unit **13** illustrated in FIG. **1** and the control unit **13** executes the angular displacement detecting method by reading the program.

In the adaptive optics system **10**, initial processing of the control unit **13** is first performed (step S**11**). In this initial processing step S**11**, for example, the securement of a memory region necessary for a calculation process, initial setting of parameters, etc. are performed. Also, in step S**11**, the center of the region B**1** or B**2** may be designated in any pixel of the modulation surface **11***a* as the initial processing of the special phase pattern P_A for detecting the angular displacement amount.

Next, the control unit **13** creates the special phase pattern P_A for detecting the angular displacement amount and displays the created special phase pattern P_A on the modulation surface **11***a* (step S**12**). In this step S**12**, the phase pattern (for example, see FIG. **18**) having linearity in at least one direction is displayed in the regions B**1** and B**2** on the modulation surface **11***a* corresponding to two lenses **124** of the plurality of lenses **124** of the lens array **120** and the spatially non-linear phase pattern (for example, see FIGS. **12** to **15**) is displayed in the region B**3** surrounding the regions B**1** and B**2**.

Subsequently, the control unit **13** acquires the light intensity distribution data (hereinafter referred to as light intensity distribution data D_A) through the image sensor **122** in a state in which the above-described phase pattern P_A is displayed (step S**13**, light intensity distribution acquiring step).

Subsequently, the control unit **13** specifies position coordinates of each converging spot P by calculating centers of gravity of two converging spots P included in the light intensity distribution data D_A (step S**14**). Position coordinates (xp, yp) of the converging spot P are expressed by the following Formulas (6). Also, A_{ij} denotes a light intensity at coordinates (i, j) of the light intensity distribution data D_A and R**0** denotes a calculation target region in which the converging spot P can be present in the image sensor **122**.

[Math 6]

$$xp = \frac{\sum_{i,j \subset R_0} iA_{ij}}{\sum_{i,j \subset R_0} A_{ij}} \qquad (6)$$

$$yp = \frac{\sum_{i,j \subset R_0} jA_{ij}}{\sum_{i,j \subset R_0} A_{ij}}$$

Also, before the center of gravity is calculated, processing of a threshold value, noise reduction, or the like may be performed in the light intensity distribution data D_A.

Subsequently, the control unit **13** calculates an amount of angular displacement between the modulation surface **11***a* and the wavefront sensor **12** according to the principle illustrated in FIG. **11** based on a relative relation between position coordinates of two converging spots P calculated in step S**14** (step S**15**, angle calculation step).

Thereafter, the control unit **13** may adjust an angle around the optical image La of at least one of the modulation surface **111***a* and the wavefront sensor **12** so that the angular displacement amount calculated in step S**15** is reduced (step S**16**, adjusting step). This adjustment, for example, is performed by adjusting one or both of a mounting angle of the spatial light modulator **11** and a mounting angle of the wavefront sensor **12**. In addition, because the correspondence relation between the regions B**1** and B**2** and the two converging spots P is normally eliminated by this angular adjustment, the above-described steps S**12** to S**16** may be iterated. If the angular displacement amount calculated in step S**15** is substantially zero, the angular displacement is completed.

Effects obtained by the angular displacement detecting method for the adaptive optics system **10** and the adaptive optics system **10** according to this embodiment described above will be described. In this embodiment, in the light intensity distribution acquiring step S**13**, the light intensity distribution data DA is acquired by the image sensor **122** of the wavefront sensor **12** in a state in which the phase pattern having linearity in at least one direction is displayed in the regions B**1** and B**2** of the spatial light modulator **11** and the spatially non-linear phase pattern is displayed in the region B**3** surrounding the regions B**1** and B**2**. In the light intensity distribution data DA, the converging spots P corresponding to the regions B**1** and B**2** are formed, but the relative positional relation between the converging spots P changes according to the amount of angular displacement between the modulation surface **11***a* and the wavefront sensor **12**. Accordingly, it is possible to detect the amount of angular displacement between the modulation surface **11***a* and the wavefront sensor **12** based on the relative positional relation between the converging spots P corresponding to the regions B**1** and B**2**.

Also, in this embodiment, it is possible to easily and quickly detect the amount of angular displacement according to only an operation of the control unit **13** without requiring the special component or structure for detecting the angular displacement amount. Also, in the method disclosed in the above-described Non Patent Literature 2, the phase pattern structure is complex and not easy to create. On the other hand, in this embodiment, it is only necessary for the phase pattern P_A to include the regions B**1** to B**3** formed of a simple phase pattern, a structure of the phase

pattern is easy, and the creation of the phase pattern by the control unit **13** is also easy. In addition, in the method disclosed in Non Patent Literature 2, it is necessary to calculate the entire wavefront shape based on the light intensity distribution data output from the wavefront sensor **12**. On the other hand, the calculation process is facilitated because the angular displacement amount can be detected based on only a part of the light intensity distribution data in this embodiment.

As described above, it is possible to easily detect an amount of angular displacement about the optical axis between the modulation surface **11***a* and the wavefront sensor **12** and perform angular adjustment according to the angular displacement detecting method of this embodiment and the adaptive optics system **10**.

Also, the sizes of the regions B**1** and B**2** are set so that the size of a wavefront part A**4** (see FIG. **7**) matches a diameter of the lens **124** (see Formula (5)) in this embodiment. However, the sizes of the regions B**1** and B**2** are not limited thereto, and, for example, may be set so that a length of one side of the wavefront part A**4** becomes n_1 (n_1 is a natural number) times the diameter of the lens **124**. In this case, assuming that an array pitch of the pixels **11***b* in the modulation surface **11***a* is denoted by slmPITCH, an array pitch of the lenses **124** in the lens array **120** is denoted by mlaPITCH, and imaging magnification of an optical system between the modulation surface **11***a* and the lens surface of the lens array **120** is denoted by M, the number of pixels w of one side of the region B**1** or B**2** is expressed by the following Formula (7).

[Math 7]

$$w = \frac{n_1}{M} \times \frac{mlaPITCH}{slmPITCH} \tag{7}$$

In other words, a width (=w×slmPITCH) of the region B**1** or B**2** in an array direction of the plurality of lenses **124** can be (n_1/M) times the array pitch mlaPITCH of the plurality of lenses **124**.

(Second Embodiment)

In the above-described first embodiment, the light intensity distribution data D_A is acquired in a state in which the first phase pattern having linearity in at least one direction is displayed in the regions B**1** and B**2** in the light intensity distribution acquiring step S**13**. However, it is not necessarily necessary to simultaneously display the first phase pattern to be displayed in the regions B**1** and B**2**, and the above-described embodiment can be modified as follows.

FIG. **21** is a flowchart illustrating an angular displacement detecting method and an operation of a control unit **13** according to the second embodiment. A difference between this embodiment and the above-described first embodiment is that steps S**21** to S**24** are provided instead of steps S**12** and S**13** illustrated in FIG. **20**. Also, because the other steps are similar to those of the above-described first embodiment, detailed description thereof will be omitted.

In step S**21**, the control unit **13** creates a special phase pattern P_B for detecting an angular displacement amount and displays the created special phase pattern P_B on the modulation surface **11***a*. FIG. **22** is a diagram conceptually illustrating the phase pattern P_B of this modified example. As illustrated in FIG. **22**, in the phase pattern P_B, the first phase pattern (for example, see FIG. **18**) having linearity in at least one direction is displayed in the first region B**1** on the modulation surface **11***a*. Also, simultaneously, a spatially non-linear second phase pattern (for example, see FIGS. **12** to **15**) is displayed in a region B**4** surrounding the first region B**1** on the modulation surface **11***a*.

Subsequently, in step S**22**, the control unit **13** acquires the first light intensity distribution data (hereinafter referred to as light intensity distribution data D_B) through the image sensor **122** in a state in which the above-described phase pattern P_B is displayed (first light intensity distribution acquiring step). In this first light intensity distribution data D_B, a converging spot P corresponding to the region B**1** is included.

Subsequently, in step S**23**, the control unit **13** creates a special phase pattern P_C for detecting an angular displacement amount and displays the created special phase pattern P_C on the modulation surface **11***a*. FIG. **23** is a diagram conceptually illustrating the phase pattern P_C of this modified example. As illustrated in FIG. **23**, in the phase pattern P_C, the first phase pattern (for example, see FIG. **18**) having linearity in at least one direction is displayed in the second region B**2** on the modulation surface **11***a*. Also, simultaneously, a spatially non-linear second phase pattern (for example, see FIGS. **12** to **15**) is displayed in a region B**5** surrounding the second region B**2** on the modulation surface **11***a*.

Subsequently, in step S**24**, the control unit **13** acquires the second light intensity distribution data (hereinafter referred to as light intensity distribution data D_C) through the image sensor **122** in a state in which the above-described phase pattern P_C is displayed (second light intensity distribution acquiring step). In this second light intensity distribution data D_C, a converging spot P corresponding to the region B**2** is included.

Thereafter, the control unit **13** specifies position coordinates of a converging spot P included in each of two pieces of light intensity distribution data D_B and Dc (step S**14**), and calculates an amount of angular displacement between the modulation surface **11***a* and the wavefront sensor **12** based on a relative positional relation between the position coordinates (angle calculating step S**15**). Also, even in this embodiment, the control unit **13** may adjust an angle around the optical image La of at least one of the modulation surface **11***a* and the wavefront sensor **12** so that the angular displacement amount calculated in step S**15** is reduced (adjusting step S**16**).

As in this embodiment, the first light intensity distribution data D_B including the converging spot P corresponding to the first region B**1** and the second light intensity distribution data Dc including the converging spot P corresponding to the second region B**2** may be sequentially acquired, and a relative positional relation between the two converging spots P may be obtained from the light intensity distribution data D_B and D_C. Even in this method, the same effects as those of the above-described first embodiment can be obtained.

(Third Embodiment)

In the above-described first and second embodiments, the first phase pattern having linearity in at least one direction is displayed in two regions B**1** and B**2** and an amount of angular displacement is obtained based on a relative positional relation between converging spots P corresponding to the regions B**1** and B**2**. In the angular displacement detecting method and the adaptive optics system **10** according to an aspect of the present invention, it is possible to obtain the angular displacement amount even in a method to be described below. Also, the configuration of the adaptive

optics system **10** is similar to that of the above-described first embodiment except for the operation of the control unit **13**.

FIG. **24** is a diagram conceptually illustrating a special phase pattern P_D for detecting an amount of angular displacement to be displayed on the modulation surface **11***a* in this embodiment. As illustrated in FIG. **24**, the phase pattern P_D includes three regions B**6** to B**8** adjacent to one another arranged in a line in a certain direction. In addition, the phase pattern P_D includes a region B**9** surrounding the regions B**6** to B**8**. Also, a length of one side of each of the regions B**6** to B**8** is similar to those of the regions B**1** and B**2** of the above-described first and second embodiments.

FIG. **25**(*a*) is a diagram conceptually illustrating a relative relation between the regions B**6** to B**8** and the lens array **120** and illustrates the case in which there is no angular displacement between the modulation surface **11***a* and the wavefront sensor **12** and the case in which there is no positional displacement between the modulation surface **11***a* and the wavefront sensor **12**. FIG. **25**(*b*) is a diagram illustrating light intensity distribution data D_D in the case illustrated in FIG. **25**(*a*). Also, in these drawings, an arrow An denotes a row direction of the modulation surface **11***a* and an arrow Am denotes a column direction of the modulation surface **11***a*. As illustrated in FIG. **25**(*b*), converging spots P corresponding to the regions B**6** to B**8** are clearly shown in the light intensity distribution data D_D when angular displacement and positional displacement between the modulation surface **11***a* and the wavefront sensor **12** are absent. Also, in the drawing of this embodiment, a clear converging spot P is denoted by a black dot.

On the other hand, FIG. **26**(*a*) illustrates the case in which angular displacement (displacement amount θ) occurs between the modulation surface **11***a* and the wavefront sensor **12**. In this case, as illustrated in FIG. **26**(*b*), the clarity of the converging spot P corresponding to the region B**7** positioned at the rotation center does not change in the light intensity distribution data D_D, but the clarity of the converging spots P corresponding to the regions B**6** and B**8** positioned above and below the region B**7** is degraded. In addition, because light is also incident on an adjacent lens **124** in a direction of angular displacement with respect to the lenses **124** corresponding to the regions B**6** and B**8**, a weak converging spot P is formed by these lenses **124**. Also, in the drawing of this embodiment, the converging spot P having slightly degraded clarity is denoted by a white dot and the weak converging spot P is denoted by a broken line. Accordingly, it is possible to detect an amount θ of angular displacement between the modulation surface **11***a* and the wavefront sensor **12** based on the relative positional relation and clarity of these converging spots P.

Further, FIG. **27**(*a*) illustrates the case in which positional displacement occurs within a plane perpendicular to an optical axis of the optical image La in addition to angular displacement (displacement amount θ) between the modulation surface **11***a* and the wavefront sensor **12**. In this case, as illustrated in FIG. **27**(*b*), the clarity of the converging spot P corresponding to the region B**7** is also degraded because the center region B**7** is also displaced from a predetermined position. In addition, because light is also incident on the lenses **124** located in a direction of positional displacement of the regions B**6** to B**8**, a plurality of weak converging spots P are formed by these lenses **124**. Thereby, the adjustment of relative positions of the modulation surface **11***a* and the wavefront sensor **12** is performed based on such light intensity distribution data D_D and thereafter it is possible to perform angular adjustment between the modulation surface **11***a* and the wavefront sensor **12**.

FIG. **28** is a flowchart illustrating an angular displacement detecting method and an operation of the control unit **13** according to this embodiment. Also, the angular displacement detecting method is stored as a program for the adaptive optics system inside the storage region **13***a* of the control unit **13** illustrated in FIG. **1** and the control unit **13** executes the angular displacement detecting method by reading the program.

In the adaptive optics system **10**, initial processing of the control unit **13** is performed (step S**31**). Also, details of step S**31** are similar to those of step S**11** of the above-described first embodiment.

Next, the control unit **13** creates the special phase pattern P_D for detecting the angular displacement amount and displays the created special phase pattern P_D on the modulation surface **11***a* (step S**32**). In this step S**32**, the phase pattern (for example, see FIG. **18**) having linearity in at least one direction is displayed in the regions B**6** to B**8** on the modulation surface **111***a* corresponding to three lenses **124** arranged in a line among the plurality of lenses **124** of the lens array **120** and the spatially non-linear phase pattern (for example, see FIGS. **12** to **15**) is displayed in a region B**9** surrounding the regions B**6** to B**8**.

Subsequently, the control unit **13** acquires the light intensity distribution data D_D through the image sensor **122** in a state in which the above-described phase pattern PD is displayed (step S**33**). Normally, at this time, the light intensity distribution data D_D becomes as in FIG. **27**(*b*) because both the angular displacement and the positional displacement occur between the modulation surface **11***a* and the wavefront sensor **12**. The control unit **13** adjusts the positional displacement between the modulation surface **11***a* and the wavefront sensor **12** so that the converging spot P corresponding to any one of the regions B**6** to B**8** (for example, the center region B**7**) of the light intensity distribution data D_D is clear (step S**34**). Also, this adjustment of positional displacement is performed by adjusting a relative relation between a mounting position of the wavefront sensor **12** and a mounting position of the spatial light modulator **11**. Alternatively, the adjustment of the positional displacement may be performed according to the adjustment of a relative positional relation between position coordinates assumed on the modulation surface **11***a* when the phase pattern P_D is displayed and the wavefront sensor **12**.

Subsequently, the control unit **13** acquires the light intensity distribution data D_D through the image sensor **122** in a state in which the above-described phase pattern P_D is displayed (step S**35**, light intensity distribution acquiring step). Because the positional displacement between the modulation surface **11***a* and the wavefront sensor **12** is already adjusted in the above-described step S**34**, the light intensity distribution data D_D at that time becomes as in FIG. **26**(*b*). The control unit **13** obtains an amount θ of angular displacement between the modulation surface **11***a* and the wavefront sensor **12** based on a relative relation between position coordinates and clarity of a plurality of converging spots P corresponding to the region B**6** and position coordinates and clarity of a plurality of converging spots P corresponding to the region B**8** included in the light intensity distribution data D_D (step S**36**, angle calculating step).

Subsequently, the control unit **13** may adjust an angle around the optical image La of at least one of the modulation surface **11***a* and the wavefront sensor **12** so that the angular displacement amount θ obtained in step S**36** is reduced (step S**16**, adjusting step). In other words, these angles are

adjusted so that the clarity of two converging spots P corresponding to the regions B**6** and B**8** increases and a weak converging spot P adjacent to the converging spots P corresponding to the regions B**6** and B**8** is reduced. This adjustment, for example, is performed by adjusting one or both of a mounting angle of the spatial light modulator **11** and a mounting angle of the wavefront sensor **12**.

Normally, the positional displacement between the modulation surface **11***a* and the wavefront sensor **12** is caused by the angular adjustment of step S**37**. Accordingly, the above-described steps S**33** to S**37** are iterated until a predetermined termination condition is satisfied (step S**38**). Alternatively, if position coordinates assumed on the modulation surface **11***a* are adjusted when the phase pattern P_D is displayed, the above-described steps S**32** to S**37** are iterated until a predetermined termination condition is satisfied (step S**38**). If the positional displacement and the angular displacement between the modulation surface **11***a* and the wavefront sensor **12** are substantially zero (see FIG. **25**(*b*)), the displacement is completed.

Effects obtained by the angular displacement detecting method for the adaptive optics system **10** and the adaptive optics system **10** according to this embodiment described above will be described. In this embodiment, in the light intensity distribution acquiring step S**35**, the light intensity distribution data D_D is acquired by the image sensor **122** of the wavefront sensor **12** in a state in which the phase pattern having linearity in at least one direction is displayed in the regions B**6** to B**8** of the spatial light modulator **11** and the spatially non-linear phase pattern is displayed in the region B**9** surrounding the regions B**6** to B**8**. In the light intensity distribution data D_D, the converging spots P corresponding to the regions B**6** to B**8** are formed, but the relative positional relation between the converging spots P (particularly, the converging spots P corresponding to the regions B**6** to B**8**) changes according to the amount of angular displacement between the modulation surface **11***a* and the wavefront sensor **12**. Accordingly, it is possible to detect the amount of angular displacement between the modulation surface **11***a* and the wavefront sensor **12** based on the relative positional relation between the converging spots P corresponding to the regions B**6** to B**8**. In addition, in this embodiment, as in the first embodiment, it is possible to easily and quickly detect the amount of angular displacement according to only an operation of the control unit **13** without requiring the special component or structure for detecting the angular displacement amount.

Also, in this embodiment, in the light intensity distribution acquiring step S**35**, the light intensity distribution data D_D is acquired in a state in which the first phase pattern having linearity in at least one direction is displayed in the regions B**6** to B**8**. However, it is not necessarily necessary to simultaneously display the first phase patterns to be displayed in the regions B**6** to B**8**. As in the second embodiment, the light intensity distribution data may be acquired while the first phase patterns are sequentially displayed in the regions B**6** to B**8** and the process of step S**36** may be performed based on three pieces of obtained light intensity distribution data.

(Fourth Embodiment)

All the above-described first to third embodiments relate to an amount of angular displacement between the modulation surface **11***a* and the wavefront sensor **12**. In this embodiment, an imaging magnification detecting method for an adaptive optics system **10** and the adaptive optics system **10** including the method and operation common to the first to third embodiments will be described. Also, in this embodiment, the configuration of the adaptive optics system **10** is similar to that of the above-described first embodiment except for the operation of the control unit **13**.

FIG. **29** is a flowchart illustrating the imaging magnification detecting method and the operation of the control unit **13** according to this embodiment. Also, the imaging magnification detecting method is stored as a program for the adaptive optics system inside the storage region **13***a* of the control unit **13** illustrated in FIG. **1** and the control unit **13** executes the imaging magnification detecting method by reading the program.

In the adaptive optics system **10**, initial processing of the control unit **13** is performed (step S**41**). Also, details of step S**41** are similar to those of step S**11** of the above-described first embodiment.

Next, the control unit **13** creates the special phase pattern P_A (see FIG. **8**) for detecting imaging magnification and displays the created special phase pattern P_A on the modulation surface **11***a* (step S**42**). Also, details of the phase pattern P_A are similar to those of the first embodiment. Thereafter, the control unit **13** acquires the light intensity distribution data D_A through the image sensor **122** in a state in which the above-described phase pattern P_A is displayed (step S**43**, light intensity distribution acquiring step).

Subsequently, the control unit **13** specifies position coordinates (xp, yp) of each converging spot P by calculating centers of gravity of two converging spots P included in the light intensity distribution data D_A (step S**44**). Also, a method of calculating the position coordinates (xp, yp) of the converging spot P is similar to step S**14** of the above-described first embodiment. Here, the position coordinates of the converging spot P corresponding to the region B**1** are designated as (xp_1, yp_1) and the position coordinates of the converging spot P corresponding to the region B**2** are designated as (xp_2, yp_2).

Subsequently, the control unit **13** calculates imaging magnification M between the modulation surface **11***a* and the wavefront sensor **12** based on a distance between the position coordinates (xp_1, yp_1) of the converging spot P corresponding to the region B**1** and the position coordinates (xp_2, yp_2) of the converging spot P corresponding to the region B**2** (step S**45**, magnification calculating step). Here, when the distance between the position coordinates (xp_1, yp_1) and the position coordinates (xp_2, yp_2) is designated as H**1** and a distance between the center position (xc_1, yc_1) of the region B**1** and the center position (xc_2, yc_2) of the region B**2** is designated as H**2**, the imaging magnification M is obtained according to a ratio (H**1**/H**2**). In other words, the imaging magnification M is obtained according to the following Formula (8).

[Math 8]

$$M = \frac{\sqrt{(xp_2 - xp_1)^2 + (yp_2 - yp_1)^2}}{\sqrt{(xc_2 - xc_1)^2 + (yc_2 - yc_1)^2}} \tag{8}$$

Thereafter, various adjustments are performed based on the imaging magnification M calculated in step S**45** (step S**46**). For example, it is possible to adjust the magnification of a light guide optical system (for example, lenses **15** and **16** illustrated in FIG. **1**) arranged between the modulation surface **11***a* and the wavefront sensor **12** so that the imaging magnification M calculated in step S**45** is close to predetermined imaging magnification. This adjustment can be

applied when the light guide optical system is constituted of a zoom lens in which the imaging magnification M is variable, etc. Also, because there is a possibility of displacement of a relative position of an optical axis direction between the modulation surface **11***a* and the wavefront sensor **12** when the imaging magnification M is displaced from the predetermined imaging magnification, for example, it is possible to adjust an optical distance between the modulation surface **11***a* and the wavefront sensor **12** so that the imaging magnification M calculated in step **S45** is close to the predetermined imaging magnification. In addition, for example, it is also possible to adjust a size of a region in which a phase pattern for compensating for wavefront distortion is displayed on the modulation surface **11***a* based on the imaging magnification M calculated in step **S45**.

Effects obtained by the imaging magnification detecting method for the adaptive optics system **10** and the adaptive optics system **10** according to this embodiment described above will be described. In this embodiment, in the light intensity distribution acquiring step **S43**, the light intensity distribution data DA is acquired by the image sensor **122** of the wavefront sensor **12** in a state in which the phase pattern having linearity in at least one direction is displayed in the regions B**1** and B**2** of the spatial light modulator **11** and the spatially non-linear phase pattern is displayed in the region B**3** surrounding the regions B**1** and B**2**. In the light intensity distribution data D_A, the converging spots P corresponding to the regions B**1** and B**2** are formed, but the distance between the converging spots P changes according to the imaging magnification M between the modulation surface **11***a* and the wavefront sensor **12**. Accordingly, it is possible to detect the imaging magnification M between the modulation surface **11***a* and the wavefront sensor **12** based on the distance between the converging spots P corresponding to the regions B**1** and B**2**. In addition, in this embodiment, it is possible to easily and quickly detect the imaging magnification M according to only an operation of the control unit **13** without requiring the special component or structure for detecting the imaging magnification M.

(Fifth Embodiment)

In the above-described fourth embodiment, the light intensity distribution data D_A is acquired in a state in which the first phase pattern having linearity in at least one direction is displayed in the regions B**1** and B**2** in the light intensity distribution acquiring step **S43**. However, it is not necessarily necessary to simultaneously display the first phase pattern to be displayed in the regions B**1** and B**2** as in the second embodiment in the imaging magnification detecting method either.

FIG. **30** is a flowchart illustrating the imaging magnification detecting method and the operation of the control unit **13** according to the fifth embodiment. A difference between this embodiment and the above-described first embodiment is that steps **S51** to **S54** are provided instead of steps **S42** and **S43** illustrated in FIG. **29**. Also, because the other steps are similar to those of the above-described fourth embodiment, detailed description thereof will be omitted.

In step **S51**, the control unit **13** creates a special phase pattern P_B (see FIG. **22**) for detecting the imaging magnification and displays the created special phase pattern P_B on the modulation surface **11***a*. Details of the phase pattern P_B are similar to those of the second embodiment. Thereafter, in step **S52**, the control unit **13** acquires the first light intensity distribution data D_B through the image sensor **122** in a state in which the above-described phase pattern P_B is displayed (first light intensity distribution acquiring step). The converging spot P corresponding to the region B**1** is included in the first light intensity distribution data D_B.

Subsequently, in step **S53**, the control unit **13** creates a special phase pattern P_C (see FIG. **23**) for detecting the imaging magnification and displays the created special phase pattern P_C on the modulation surface **11***a*. Also, details of the phase pattern P_C are similar to those of the second embodiment. Thereafter, in step **S54**, the control unit **13** acquires second light intensity distribution data Dc through the image sensor **122** in a state in which the above-described phase pattern P_C is displayed (second light intensity distribution acquiring step). The converging spot P corresponding to the region B**2** is included in the second light intensity distribution data D_C.

Thereafter, the control unit **13** specifies position coordinates of converging spots P included in two pieces of light intensity distribution data D_B and D_C obtained in steps **S51** to **S54** (step **S44**) and calculates imaging magnification M between the modulation surface **11***a* and the wavefront sensor **12** based on a distance between the position coordinates (magnification calculating step **S45**). Thereafter, various adjustments are performed in step **S46**.

As in this embodiment, the first light intensity distribution data D_B including the converging spot P corresponding to the first region B**1** and the second light intensity distribution data Dc including the converging spot P corresponding to the second region B**2** may be sequentially acquired and a distance between the two converging spots P may be obtained from the light intensity distribution data D_B and D_c. Even in this method, similar effects to the above-described fourth embodiment can be obtained.

FIRST MODIFIED EXAMPLE

Although the case in which the first region B**1** and the second region B**2** are regions separated from each other is shown in the above-described embodiments except the third embodiment, for example, the first region B**1** and the second region B**2** may be regions adjacent to each other in a row or column direction as illustrated in FIGS. **31**(*a*) and **31**(*b*). Alternatively, for example, as illustrated in FIG. **32**, the first region B**1** and the second region B**2** may be regions adjacent to each other in a diagonal direction. Even when the regions B**1** and B**2** are arranged as described above, it is possible to obtain similar effects to the above-described embodiments. However, when the regions B**1** and B**2** are separated from each other, corresponding converging spots P are unlikely to overlap each other. Accordingly, the regions B**1** and B**2** may be separated from each other according to a shape of a first phase pattern having linearity.

SECOND MODIFIED EXAMPLE

In the above-described embodiment, the first phase pattern having the linearity in at least one direction is displayed in the regions B**1** and B**2** (or the regions B**6** to B**8**) and the spatially non-linear second phase pattern is displayed in the regions B**3** to B**5** (or the region B**9**). However, even when the first phase pattern having the linearity in at least one direction is displayed in the regions B**3** to B**5** (or the region B**9**) and the spatially non-linear second phase pattern is displayed in the regions B**1** and B**2** (or the regions B**6** to B**8**), it is possible to obtain similar effects to the above-described embodiments. In this case, the above-described Formula (3) is rewritten as follows.

[Math 9]

$$P_A(n, m) = \begin{cases} rand\ () & (n, m) \subset ROI \\ a & (n, m) \not\subset ROI \end{cases} \quad (9)$$

In this modified example, converging spots P corresponding to the regions B**1** and B**2** (or the regions B**6** to B**8**) become unclear and converging spots P corresponding to the regions B**3** to B**5** (or the region B**9**) around the regions B**1** and B**2** (or the regions B**6** to B**8**) become clear. In this case, it is possible to calculate the amount of angular displacement (or the imaging magnification M) between the modulation surface **11***a* and the wavefront sensor **12** based on a relative relation (or distance) between position coordinates of the converging spot P formed around the region B**1** (or the region B**6**) and position coordinates of the converging spot p formed around the region B**2** (or the region B**8**).

According to this modified example, as in the above-described embodiment, it is possible to easily detect the amount of angular displacement about the optical axis (or the imaging magnification M) between the modulation surface **11***a* and the wavefront sensor **12**.

Because the phase pattern having linearity can be displayed in all regions other than the regions B**1** and B**2** (or the regions B**6** to B**8**), it is possible to detect the amount of angular displacement about the optical axis (or the imaging magnification M) in parallel during adaptive optical execution by designating the phase pattern as a phase pattern for compensating for wavefront distortion.

THIRD MODIFIED EXAMPLE

In the above-described embodiments, a substantially uniform distribution expressed by a constant a has been shown as an example of a first phase pattern having linearity in at least one direction displayed in the regions B**1** and B**2** or B**6** to B**8** (the regions B**3** to B**5** or B**9** in the second modified example). However, the first phase pattern may be a phase distribution inclined in at least one direction (changed linearly). Also, a phase pattern P_A including the above-described phase pattern is expressed by the following Formula (10).

[Math 10]

$$P_A(n, m) = \begin{cases} a + b(n - n_0) + c(m - m_0) & (n, m) \subset ROI \\ rand\ () & (n, m) \not\subset ROI \end{cases} \quad (10)$$

Here, n_0 and m_0 denote center pixels of the regions B**1** and B**2** (ROI) and a, b, and c are constants.

FIG. **33** illustrates a phase distribution in which phase values are inclined in a first direction (for example, a row direction) and phase values are substantially uniform in a second direction (for example, a column direction) intersecting the first direction. This is a phase distribution in ROI of the case in which $b \neq 0$ and $c = 0$ in the above-described Formula (10). Also, FIG. **34** illustrates a phase distribution in which phase values are inclined in both the first direction (for example, the row direction) and the second direction (for example, the column direction). This is a phase distribution in ROI of the case in which $b \neq 0$ and $c \neq 0$ in the above-described Formula (10). Also, a graph of a phase modulation amount in one position of each of row and column directions is also illustrated in FIGS. **33** and **34**. Because the wavefront of the optical image La of the relevant part is flat when these phase patterns are displayed in the regions B**1** and B**2** or B**6** to B**8**, the clear converging spot P is formed by the lens **124**. Accordingly, as in the above-described embodiments and modified examples, it is possible to detect the angular displacement amount or the imaging magnification M based on the relative positional relation or the distance between the converging spots P.

However, in this modified example, the center of gravity position of the converging spot P is displaced by a slope of the first phase pattern. Accordingly, when the angular displacement amount or the imaging magnification M is detected, it is possible to perform similar calculation to the above-described embodiments in consideration of the displacement of a center of gravity position. Also, a displacement amount of the center of gravity position of the converging spot P is uniquely defined based on a configuration parameter of the wavefront sensor **12** and the coefficients b and c. In addition, because it is possible to obtain the original center of gravity position by subtracting the above-described displacement amount from the center of gravity position of the converging spot P, it is possible to detect the angular displacement amount or the imaging magnification M according to a similar procedure to the above-described embodiments.

FOURTH MODIFIED EXAMPLE

The first phase pattern displayed in the regions B**1** and B**2** or B**6** to B**8** (the regions B**3** to B**5** or the region B**9** in the second modified example) may be a phase distribution having a quadratic function in the first direction and in which phase values are substantially uniform in the second direction (that is, a phase distribution having the cylindrical lens effect in the first direction) as illustrated in FIG. **35**. Also, this phase pattern P_A including such a phase distribution is expressed by the following Formula (11).

[Math 11]

$$P_A(n, m) = \begin{cases} a_1 + b_1(n - n_1)^2 & (n, m) \subset ROI(n_1, m_1) \\ a_2 + b_2(n - n_2)^2 & (n, m) \subset ROI(n_2, m_2) \\ rand\ () & (n, m) \not\subset (ROI(n_1, m_1) \cup ROI(n_2, m_2)) \end{cases} \quad (11)$$

In the above-described Formula (11), n_1 and m_1 denote center pixels of the region B**1** (ROI(n_1, m_1)), n_2 and m_2 denote center pixels of the region B**2** (ROI(n_2, m_2)) and a_1, b_1, a_2, and b_2 denote constants.

When the phase pattern illustrated in FIG. **35** is displayed on the modulation surface **11***a*, a converging spot P extending in the first direction and converging in the second direction is formed in the wavefront sensor **12**. Thereby, it is possible to obtain a position of the converging spot P to be formed in the second direction. Subsequently, when the phase pattern P_A of the phase distribution (that is, a phase distribution having the cylindrical lens effect in the second direction) in which the first and second directions are interchanged is displayed on the modulation surface **11***a*, the position of the converging spot P in the first direction is obtained. Accordingly, it is possible to detect the angular displacement amount or the imaging magnification as in the above-described embodiments and first to third modified examples using the phase pattern having linearity in at least

one direction as in FIG. **35**. Alternatively, the phase pattern P_A including a phase distribution having the cylindrical lens effect can be created by the following Formula (12).

[Math 12]

$$P_A(n,m) = \begin{cases} a_1 + b_1(n-n_1)^2 & (n,m) \subset ROI(n_1,m_1) \\ a_2 + b_2(m-m_2)^2 & (n,m) \subset ROI(n_2,m_2) \\ rand\ () & (n,m) \notin (ROI(n_1,m_1) \cup ROI(n_2,m_2)) \end{cases} \quad (12)$$

The phase pattern P_A expressed by the following Formula (12) is different from the phase pattern expressed by Formula (11), has a quadratic function in the first direction in the region B**1**, and has a quadratic function in the second direction in the region B**2**. When phase pattern P_A expressed by the following Formula (12) is displayed on the modulation surface **11***a*, the position of the second direction is obtained based on the converging spot P corresponding to the region B**1**, that is, the converging spot P extending in the first direction and converging in the second direction. In addition, the position of the first direction is obtained based on the converging spot P corresponding to the region B**2**, that is, the converging spot P extending in the second direction and converging in the first direction. Subsequently, when the phase pattern P_A including phase distributions obtained by interchanging the phase distributions of the regions B**1** and B**2** (that is, a phase distribution having a quadratic function in the second direction in the region B**1** and a phase distribution having a quadratic function in the first direction in the region B**2**) is displayed on the modulation surface **11***a*, the position of the first direction is obtained based on the converging spot P extending in the second direction corresponding to the region B**1** and the position of the second direction is obtained based on the converging spot P extending in the first direction corresponding to the region B**2**. It is possible to detect the angular displacement amount or the imaging magnification as in the above-described embodiments and modified examples using positions of converging spots P corresponding to the regions B**1** and B**2**.

FIFTH MODIFIED EXAMPLE

First phase patterns displayed in regions B**1** and B**2** or B**6** to B**8** (the regions B**3** to B**5** or the region B**9** in the second modified example) may have a phase distribution constituting a diffraction grating in the first direction and in which phase values are substantially uniform in the second direction as illustrated in FIG. **36**. When the phase pattern illustrated in FIG. **36** is displayed on the modulation surface **11***a*, a plurality of converging spots P separated in the first direction and converging in the second direction are formed in the wavefront sensor **12**. Accordingly, the position of the converging spot P in the second direction is obtained. Subsequently, the position of the converging spot P in the first direction is obtained using phase patterns including phase distributions in which the direction of the diffraction grating rotates 90 degrees in the regions B**1** and B**2**. It is possible to detect the angular displacement amount or the imaging magnification as in the above-described embodiments and modified examples using positions of converging spots P corresponding to the regions B**1** and B**2**.

SIXTH MODIFIED EXAMPLE

First phase patterns displayed in regions B**1** and B**2** or B**6** to B**8** (the regions B**3** to B**5** or the region B**9** in the second modified example) may include a composite pattern in which phase distributions shown in the first embodiment and the third to fifth modified examples are mutually superimposed. FIG. **37** is a diagram illustrating an example of the composite pattern obtained by such superimposition. The phase pattern illustrated in FIG. **37**(*a*) is the phase pattern illustrated in FIG. **35** and the phase pattern illustrated in FIG. **37**(*b*) is the phase pattern obtained by rotating the phase pattern illustrated in FIG. **33** 90 degrees. The phase pattern illustrated in FIG. **37**(*c*) is a composite pattern in which the phase patterns are superimposed and is a phase pattern of a phase distribution having a quadratic function in the first direction and a linear function in the second direction. When the composite pattern illustrated in FIG. **37**(*c*) is displayed on the modulation surface **11***a*, the converging spot P extending in the first direction and converging in the second direction is formed in the wavefront sensor **12**. Accordingly, the position of the converging spot P to be formed in the second direction is obtained. Also, the displacement amount is included at the obtained position of the second direction according to an inclined phase distribution as in FIG. **37**(*b*). It is possible to obtain the original center of gravity position of the second direction by subtracting the displacement amount. Subsequently, it is possible to obtain the center of gravity position of the first direction by displaying a phase pattern obtained by rotating the phase pattern illustrated in FIG. **37**(*c*) 90 degrees. It is possible to detect the angular displacement amount or the imaging magnification as in the above-described embodiments and modified examples using positions of converging spots P corresponding to the regions B**1** and B**2**.

SEVENTH MODIFIED EXAMPLE

In the above-described embodiments and modified examples, examples of the random distribution (FIG. **12**) and the defocus distribution (FIG. **13**) are shown as an example of the spatially non-linear second phase pattern displayed in the regions B**3** to B**5** (the region B**9** in the second modified example). The second phase pattern is not limited thereto, but it is only necessary for the second phase pattern to have a phase distribution so that a clear converging spot P is not formed. As this phase distribution, for example, there is a Fresnel zone plate (FZP) type phase pattern. The FZP type phase pattern has a function of converging or diverging an incident optical image La having a substantially uniform phase value. Accordingly, when the optical image La converged or diverged by the FZP type phase pattern is incident on the lens **124**, the position of the optical axis direction of the converging spot P is displaced from a focal plane of the lens **124** (that is, the surface of the image sensor **122**). Thus, a blurred point image is formed in the surface of the image sensor **122**.

The phase pattern P_A including this FZP type phase pattern is expressed by the following Formula (13).

[Math 13]

$$P_A(n,m) = \begin{cases} a_1 + b_1(n-n_0) + c_1(m-m_0) & (n,m) \subset ROI \\ a_2 + b_2((n-n_k)^2 + (m-m_k)^2) & (n,m) \notin ROI \end{cases} \quad (13)$$

Here, a_2 denotes a constant and b_2 denotes a sufficiently large constant. (n_k, m_k) denotes center pixels of the regions B3 to B5. Also, when b_2 is sufficiently large, it is possible to sufficiently separate the converging spot P formed by the lens **124** from the focal plane of the lens **124** (the surface of the image sensor **122**).

EIGHTH MODIFIED EXAMPLE

In the above-described embodiments and modified examples, an example of a form in which the plurality of lenses **124** are arranged as the lens array **120** of the wavefront sensor **12** in the two-dimensional lattice shape as illustrated in FIG. **3** is shown. However, the lens array of the wavefront sensor **12** is not limited to such a form. For example, as illustrated in FIG. **38**, the lens array **120** may have a honeycomb structure in which a plurality of regular hexagonal lenses **128** are arranged without gaps. Also, in this case, the regions B**1** and B**2** or the regions B**6** to B**8** may be set in a hexagonal shape.

In addition, a form in which a plurality of regular hexagonal pixels are arranged without gaps may be used as the spatial light modulator. In addition, the spatial light modulator is described as an example in the above-described embodiments, but a spatial light modulator using a material having an electro-optic effect other than liquid crystal, a spatial light modulator in which a pixel is formed of a micro-mirror, a variable mirror for deforming a film mirror using an actuator, or the like may be used.

An angular displacement detecting method for an adaptive optics system, an imaging magnification detecting method for an adaptive optics system, and an adaptive optics system according to an aspect of the present invention are not limited to the above-described embodiments, and other various modifications are possible. For example, sizes of the regions B**1** and B**2** or the regions B**6** to B**8** are preset and the angular displacement amount, etc. are detected in the above-described embodiments and modified examples, but the sizes of the regions B**1** and B**2** or the regions B**6** to B**8** may be variable. FIG. **39** is a diagram illustrating an example of the case in which sizes of first and second regions B**1** and B**2** are configured to be variable. In the example illustrated in FIG. **39**(*a*), the sizes of the regions B**1** and B**2** are set to be relatively large and reduced to an appropriate size (for example, a size corresponding to the diameter of the lens **124**) based on the obtained light intensity distribution data. In addition, in the example illustrated in FIG. **39**(*b*), the sizes of the regions B**1** and B**2** are set to be relatively small and enlarged to an appropriate size (for example, a size corresponding to the diameter of the lens **124**) based on the obtained light intensity distribution data. As described above, the sizes of the regions B**1** and B**2** (or the regions B**6** to B**8**) are set to be variable, so that it is possible to set the regions B**1** and B**2** (or the regions B**6** to B**8**) having an appropriate size and further precisely detect the angular displacement amount or the imaging magnification. In addition, the phase patterns to be displayed in the regions B**1** and B**2** need not necessarily be the same. For example, the phase pattern having the cylindrical effect as in FIG. **35** may be displayed in the region B**1** and the phase pattern having the structure of the diffraction grating as in FIG. **36** may be displayed in the region. B**2**.

In addition, although the case in which the adaptive optics system includes one spatial light modulator is shown in the above-described embodiments and modified examples, the adaptive optics system may include a plurality of spatial light modulators coupled optically. When the plurality of spatial light modulators are coupled in series, it is possible to detect the angular displacement amount or the imaging magnification between one spatial light modulator and the wavefront sensor by causing one spatial light modulator to display the phase pattern P_A (or P_D) and causing the other spatial light modulator to display, for example, the substantially uniform phase pattern. In addition, when the plurality of spatial light modulators are coupled in parallel, it is possible to detect the angular displacement amount or the imaging magnification between one spatial light modulator and the wavefront sensor by causing one spatial light modulator to display the phase pattern P_A (or P_D) and causing the other spatial light modulator to display, for example, the substantially uniform phase pattern or by shielding an optical image before or after incidence on the other spatial light modulator. Such an operation is performed by each of the plurality of spatial light modulators, so that it is possible to detect amounts of angular displacement and imaging magnifications between all spatial light modulators and the wavefront sensor.

INDUSTRIAL APPLICABILITY

According to an angular displacement detecting method for an adaptive optics system and an adaptive optics system according to an aspect of the present invention, it is possible to easily detect angular displacement about an optical axis between a modulation surface of a spatial light modulator and a wavefront sensor. Also, according to an imaging magnification detecting method for an adaptive optics system and an adaptive optics system according to an aspect of the present invention, it is possible to easily detect imaging magnification between a modulation surface of a spatial light modulator and a wavefront sensor.

REFERENCE SIGNS LIST

10 Adaptive optics system
11 Spatial light modulator
11*a* Modulation surface
12 Wavefront sensor
13 Control unit
14 Beam splitter
15, **16** Relay lens
17 Control circuit unit
18 Optical detection element
120 Lens array
122 Image sensor
122*a* Light receiving surface
122*b* Pixel
124 Lens
B**1** First region
B**2** Second region
D**1**, D**2**, D_A to D_D Light intensity distribution data
La Optical image
P Converging spot
P_A to P_D Phase pattern

The invention claimed is:

1. An angular displacement detecting method for an adaptive optics system, which includes a spatial light modulator configured to spatially modulate a phase of an optical image incident on a modulation surface and a wavefront sensor including a lens array having a plurality of two-dimensionally arranged lenses and an optical detection element for detecting a light intensity distribution including converging spots formed by the lens array and configured to receive the optical image after the modulation from the

spatial light modulator and which compensates for wavefront distortion by controlling a phase pattern displayed in the spatial light modulator based on a wavefront shape of the optical image obtained from the light intensity distribution, wherein an amount of angular displacement between the modulation surface and the wavefront sensor is calculated, the angular displacement detecting method comprising:

a light intensity distribution acquiring step of acquiring the light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in first and second regions on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the first and second regions; and

an angle calculating step of obtaining the amount of angular displacement between the modulation surface and the wavefront sensor based on a relative positional relation between the converging spot corresponding to the first region and the converging spot corresponding to the second region included in the light intensity distribution obtained in the light intensity distribution acquiring step.

2. The angular displacement detecting method for the adaptive optics system according to claim **1**, further comprising:

an adjusting step of adjusting an angle around the optical image of at least one of the modulation surface and the wavefront sensor so that the amount of angular displacement calculated in the angle calculating step is reduced.

3. The angular displacement detecting method for the adaptive optics system according to claim **1**, wherein the first and second regions are regions adjacent to each other.

4. The angular displacement detecting method for the adaptive optics system according to claim **1**, wherein the first and second regions are regions separated from each other.

5. An angular displacement detecting method for an adaptive optics system, which includes a spatial light modulator configured to spatially modulate a phase of an optical image incident on a modulation surface and a wavefront sensor including a lens array having a plurality of two-dimensionally arranged lenses and an optical detection element for detecting a light intensity distribution including converging spots formed by the lens array and configured to receive the optical image after the modulation from the spatial light modulator and which compensates for wavefront distortion by controlling a phase pattern displayed in the spatial light modulator based on a wavefront shape of the optical image obtained from the light intensity distribution, wherein an amount of angular displacement between the modulation surface and the wavefront sensor is calculated, the angular displacement detecting method comprising:

a first light intensity distribution acquiring step of acquiring a first light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in a first region on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the first region;

a second light intensity distribution acquiring step of acquiring a second light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in a second region which is a region separate from the first region on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the second region; and

an angle calculating step of obtaining the amount of angular displacement between the modulation surface and the wavefront sensor based on a relative positional relation between the converging spot corresponding to the first region included in the first light intensity distribution and the converging spot corresponding to the second region included in the second light intensity distribution.

6. An imaging magnification detecting method for an adaptive optics system, which includes a spatial light modulator configured to spatially modulate a phase of an optical image incident on a modulation surface and a wavefront sensor including a lens array having a plurality of two-dimensionally arranged lenses and an optical detection element for detecting a light intensity distribution including converging spots formed by the lens array and configured to receive the optical image after the modulation from the spatial light modulator and which compensates for wavefront distortion by controlling a phase pattern displayed in the spatial light modulator based on a wavefront shape of the optical image obtained from the light intensity distribution, wherein imaging magnification between the modulation surface and the wavefront sensor is detected, the imaging magnification detecting method comprising:

a light intensity distribution acquiring step of acquiring the light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in first and second regions on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the first and second regions; and

a magnification calculating step of obtaining the imaging magnification between the modulation surface and the wavefront sensor based on a distance between the converging spot corresponding to the first region and the converging spot corresponding to the second region included in the light intensity distribution obtained in the light intensity distribution acquiring step.

7. The imaging magnification detecting method for the adaptive optics system according to claim **6**, further comprising:

an adjusting step of adjusting the magnification of a light guide optical system arranged between the modulation surface and the wavefront sensor so that the imaging magnification calculated in the magnification calculating step is close to predetermined imaging magnification.

8. The imaging magnification detecting method for the adaptive optics system according to claim **6**, further comprising:

an adjusting step of adjusting an optical distance between the modulation surface and the wavefront sensor so that the imaging magnification calculated in the magnification calculating step is close to predetermined imaging magnification.

9. The imaging magnification detecting method for the adaptive optics system according to claim 6, further comprising:

an adjusting step of adjusting a size of a region on the modulation surface in which the phase pattern for compensating for the wavefront distortion is displayed based on the imaging magnification calculated in the magnification calculating step.

10. The imaging magnification detecting method for the adaptive optics system according to claim 6, wherein the first and second regions are regions adjacent to each other.

11. The imaging magnification detecting method for the adaptive optics system according to claim 6, wherein the first and second regions are regions separated from each other.

12. An imaging magnification detecting method for an adaptive optics system, which includes a spatial light modulator configured to spatially modulate a phase of an optical image incident on a modulation surface and a wavefront sensor including a lens array having a plurality of two-dimensionally arranged lenses and an optical detection element for detecting a light intensity distribution including converging spots formed by the lens array and configured to receive the optical image after the modulation from the spatial light modulator and which compensates for wavefront distortion by controlling a phase pattern displayed in the spatial light modulator based on a wavefront shape of the optical image obtained from the light intensity distribution, wherein imaging magnification between the modulation surface and the wavefront sensor is detected, the imaging magnification detecting method comprising:

a first light intensity distribution acquiring step of acquiring a first light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in a first region on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the first region;

a second light intensity distribution acquiring step of acquiring a second light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in a second region which is a region separate from the first region on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the second region; and

a magnification calculating step of obtaining the imaging magnification between the modulation surface and the wavefront sensor based on a distance between the converging spot corresponding to the first region included in the first light intensity distribution and the converging spot corresponding to the second region included in the second light intensity distribution.

13. An adaptive optics system comprising:

a spatial light modulator configured to spatially modulate a phase of an optical image incident on a modulation surface;

a wavefront sensor including a lens array having a plurality of two-dimensionally arranged lenses and an optical detection element for detecting a light intensity distribution including converging spots formed by the lens array and configured to receive the optical image after the modulation from the spatial light modulator; and

a control unit configured to compensate for wavefront distortion by controlling a phase pattern displayed in the spatial light modulator based on a wavefront shape of the optical image obtained from the light intensity distribution,

wherein the control unit acquires the light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in first and second regions on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the first and second regions and obtains the amount of angular displacement between the modulation surface and the wavefront sensor based on a relative positional relation between the converging spot corresponding to the first region and the converging spot corresponding to the second region included in the light intensity distribution.

14. An adaptive optics system comprising:

a spatial light modulator configured to spatially modulate a phase of an optical image incident on a modulation surface;

a wavefront sensor including a lens array having a plurality of two-dimensionally arranged lenses and an optical detection element for detecting a light intensity distribution including converging spots formed by the lens array and configured to receive the optical image after the modulation from the spatial light modulator; and

a control unit configured to compensate for wavefront distortion by controlling a phase pattern displayed in the spatial light modulator based on a wavefront shape of the optical image obtained from the light intensity distribution,

wherein the control unit acquires a first light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in a first region on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the first region, acquires a second light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in a second region which is a region separate from the first region on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the second region, and obtains the amount of angular displacement between the modulation surface and the wavefront sensor based on a relative positional relation between the converging spot corresponding to the first region included in the first light intensity distribution and the converging spot corresponding to the second region included in the second light intensity distribution.

15. An adaptive optics system comprising:

a spatial light modulator configured to spatially modulate a phase of an optical image incident on a modulation surface;

a wavefront sensor including a lens array having a plurality of two-dimensionally arranged lenses and an optical detection element for detecting a light intensity distribution including converging spots formed by the lens array and configured to receive the optical image after the modulation from the spatial light modulator; and

a control unit configured to compensate for wavefront distortion by controlling a phase pattern displayed in the spatial light modulator based on a wavefront shape of the optical image obtained from the light intensity distribution,

wherein the control unit acquires the light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in first and second regions on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the first and second regions, and obtains the imaging magnification between the modulation surface and the wavefront sensor based on a distance between the converging spot corresponding to the first region and the converging spot corresponding to the second region included in the light intensity distribution.

16. An adaptive optics system comprising:

a spatial light modulator configured to spatially modulate a phase of an optical image incident on a modulation surface;

a wavefront sensor including a lens array having a plurality of two-dimensionally arranged lenses and an optical detection element for detecting a light intensity distribution including converging spots formed by the lens array and configured to receive the optical image after the modulation from the spatial light modulator; and

a control unit configured to compensate for wavefront distortion by controlling a phase pattern displayed in the spatial light modulator based on a wavefront shape of the optical image obtained from the light intensity distribution,

wherein the control unit acquires a first light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in a first region on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the first region, acquires a second light intensity distribution through the optical detection element in a state in which one of a phase pattern having linearity in at least one direction and a spatially non-linear phase pattern is displayed in a second region which is a region separate from the first region on the modulation surface corresponding to one of the plurality of lenses or two or more lenses adjacent to each other and the other is displayed in a region surrounding the second region, and obtains the imaging magnification between the modulation surface and the wavefront sensor based on a distance between the converging spot corresponding to the first region included in the first light intensity distribution and the converging spot corresponding to the second region included in the second light intensity distribution.

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